Addressing Projected Climate Change Risk to Water Quality in Ireland

Key Findings and Policy Recommendations

Prepared By:

Karen Taylor, Marcel Jansen, Jean O'Dwyer, Tim Sullivan, John Weatherill, Simon Harrison, Andre Banning & Michelle McKeown.

University College Cork

November 2022

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

The Water Forum
An Fóram Uisce

Addressing Projected Climate Change Risk to Water Quality in Ireland

Key Findings and Policy Recommendations

Dr Karen J. Taylor

School of Biological, Earth & Environmental Sciences,
University College Cork,
Cork, Ireland.

Email: karen.jantaylor2@gmail.com

Dr Michelle M. McKeown

School of Biological, Earth & Environmental Sciences,
University College Cork,
Cork, Ireland.

Email: mmckeown@ucc.ie

Compiled for

The Water Forum
AN FÓRAM UISCE

November 2022

Table of Contents

List of Figures

List of Tables

Executive Summary

There is growing concern surrounding the important linkages between water quality and climate change. The availability of high-quality freshwater is crucial for enabling good public health, a functioning environment, and a productive economy. Over 80% of Ireland's water supply comes from surface waters (lakes, rivers, and streams), which is used for domestic drinking water supply, wastewater treatment, irrigation, industrial activities, hydropower generation, while also being an important resource for fishing and recreational activities. In addition, around 750,000 people rely on private groundwater sources for daily domestic use. Impaired water quality is a persistent and growing problem in Ireland, increasing costs associated with drinking water and food production, along with degrading ecosystems.

The Intergovernmental Panel on Climate Change Sixth Assessment Report and the Climate Status Report for Ireland 2021 predict changes in seasonality and precipitation patterns, along with an increased incidence of extreme weather events. Extreme weather events are expected to include extended periods of abnormally low precipitation (droughts), rapid high-intensity precipitation events and flooding, along with increased heat waves and storm activity. In Ireland, observed changes in climate indicate that seasonal shifts in temperature and precipitation patterns are emerging across a clear west-to-east divide. Projected changes in seasonal precipitation suggest an increase in the frequency of rapid high-intensity precipitation events during the autumn and winter months, mostly affecting the south and west coast of Ireland. A substantial reduction in precipitation during the spring and summer months is projected, which will likely result in extended periods of water stress during the summer months, mostly affecting, but not exclusive to, the east and southeast of the country. The number of heatwave events are expected to increase over the 20-year period (2041–2060), with the largest increases in the southeast of the country. Furthermore, annual reduced river discharges, associated with increased low flow periods are already evident in the east and south of Ireland, while the midlands, west and north largely show a pattern towards increasing flows.

The quality of water will be affected at different times of the year and in different parts of the country. For example, heavy rainfall events could put pressure on water infrastructure, particularly for combined sewage overflow systems in urban areas (i.e., Dublin, Cork and Galway city). Ordinarily in urban centres all the waste water is treated before discharge; however heavy rains can overwhelm combined sewage overflow systems by contributing additional stormwater, and in order to avoid sewers becoming overwhelmed in high rainfall events, excess water is discharged straight into local receiving waters, sending with it a cocktail of pathogens, active pharmaceutical ingredients, household chemicals, heavy metals, hydrocarbons, pesticides, excess nutrients, and other pollutants. However, the effect on water quality depends on a combination of climate change at the regional- to local scale, time of year (i.e., autumn and winter versus spring and summer months), population growth, and aging infrastructure. Conversely, reduced precipitation may lead to less dilution of contaminants present in water, resulting in the concentration of pollutant levels above 'Environmental Quality Standards' (EQS). In rivers and lakes, warmer summer temperatures may exacerbate the effects of eutrophication (excessive growth of plants and algae due to the increased availability of photosynthetic growing factors) and increase the abundance of cyanobacterial blooms. Some cyanobacteria produce cyanotoxins (secondary metabolites), which threaten the safe use of water for drinking and recreational (and even tourism) activities. A more complex scenario involves disentangling the combined impacts of temperature and precipitation change. For example, concentrations of organic carbon in streams and rivers draining upland peatlands have increased rapidly in recent decades due to a combination of changes in atmospheric deposition chemistry and peat degradation. The peatlands responsible for supplying high volumes of potable water in Ireland are all situated in upland areas (at least 300 m above sea level). Ireland consumes 0.19 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 4.22 million people in Ireland. Projected climate change (warmer temperatures and modified precipitation) to 2100 is predicted to cause severe degradation (drying) of peatlands, resulting in accelerated peat decomposition, release of aquatic carbon and a reduction water quality draining peat dominated systems. This will likely increase costs associated with disinfecting potable water in treatment plants, which will be required to not only remove organic carbon but also to mitigate the production of harmful disinfection by-products during the chlorination process, some of which are harmful to human health, such as trihalomethanes (THMs).

In addition to climate change, pressures from population growth and demographic and societal change (e.g. urbanisation, agricultural intensification), along with aging water infrastructure will compound existing pressures on the water sector. The population of Ireland has grown by 7.6% since 2016 and this growth is evident across every county. The impacts of climate change should inform investment in planning and ensure our infrastructure, and population, are more resilient to the realities of shifting regional weather patterns. It is essential that international initiatives, European legislation, and national strategies that promote policy responses to the water quality challenge are inclusive of climate change. This holds particularly true for the attainment of the 2030 Agenda and Sustainable Development Goals.

Effective action to integrate climate adaptation plans for water quality must be fully comprehensive to ensure the right measures are put in place to address the interconnected pressures of anthropogenic pollution, degradation of the quality of water, and climate change. To achieve this, coherence in policy documents and plans is essential. This requires identifying where water and climate policies align and diverge with scientific evidence. This information can be used to coordinate national efforts to maximise the capacity and impact of key national legislation to minimise the negative impacts of water quality in a warming world.

1. Climate Change in Ireland

Ireland's climate is changing in line with global trends (IPCC, 2021). Surface air temperature has increased by approximately 1.1°C from pre-industrial levels (IPCC, 2021; Kaufman and McKay, 2022). The Intergovernmental Panel on Climate Change (IPCC) has predicted with *high confidence* that global temperatures will further increase at a rate of 0.2°C (likely between 0.1°C and 0.3°C) per decade (IPCC, 2021). In addition to warmer surface air and water (freshwater and marine) temperatures, the IPCC Sixth Assessment Report AR6 WII (IPCC, 2022) and the Climate Status Report for Ireland (EPA, 2021a) predict changes in seasonality and precipitation patterns, increased incidence of extreme weather events and a gradual continued rise in sea level in Ireland. Extreme weather events are expected to include extended periods of abnormally low precipitation (i.e., droughts), rapid high-intensity precipitation events and flooding, heat waves, storms, and associated storm surge events, along with a reduced frost season and decreased snowfall in Ireland (Nolan and Flanagan, 2020).

The following *observed* and *projected* (future) climate change impacts are expected for Ireland:

Temperature:

- *Observed:* Mean surface air temperature has increased by 0.9°C since 1900, with 15 of the top 20 warmest days recorded occurring since 1990 (Cámaro García and Dwyer, 2021, Climate Ireland, 2022). Annual minimum air temperature has increased at a faster rate than the maximum air temperature, and this increase is greatest in the winter season (McKeown *et al.* 2012; McElwain and Sweeney, 2003). A significant latitudinal sea surface temperature gradient was observed between 1982 and 2015 in Ireland, with warmer waters reported in the south and colder in the north (Casal and Lavender, 2017). Lowest sea surface temperatures were identified in March and highest temperatures were reported in August (Casal and Lavender, 2017). The temporal and spatial heterogeneity in Irish waters is mainly related to the Atlantic Multi-decadal Oscillation (AMO) and the warming from anthropogenic CO_2 emissions (Casal and Lavender, 2017). Significant increases in sea surface temperature have been observed in some areas around Ireland (Casal and Lavender, 2017), with trends ranging from 0.28 °C to 0.20 °C per decade (Casal and Lavender, 2017).

- *Projected:* Climate projections are outlined by Nolan and Flanagan (2020) in a recent EPA report (No. 339) on 'High-resolution Climate Projections for Ireland'. To account for the uncertainty in future greenhouse gas emissions, future climate was simulated under both the Representative Concentration Pathway (RCP)4.5 and RCP8.5 scenarios between 2041 and 2060 (Nolan and Flanagan, 2020). Nolan and Flanagan (2020) outline have projected the following:
    - Average annual temperatures are projected to increase by 1–1.2°C and (RCP4.5) and 1.3–1.6°C (RCP8.5) for the respective scenarios for the 2041-2060 period.
    - Spatially, seasonal temperature is projected to increase across a clear west-to-east gradient, with the highest temperature increases projected for the east of the country (Figure 1.).
    - The number of heatwave events are expected to increase over the 20-year period (2041–2060), with the largest increases in the south-east of the country.

- The number of days where the maximum temperature is lower than 0°C is projected to decrease by 68% (RCP4.5) and 78% (RCP8.5).

Sea surface temperatures are expected to increase; however, as of yet, projected changes have not been determined with a high level of confidence for Ireland (Climate Ireland, 2022).

Precipitation and Changes in Seasonality:

- *Observed:* Annual average rainfall has increased by ~7% between 1990-2019 with the wettest period on record observed between 2006-2015. Data shows a trend of increasing winter precipitation and decreasing summer precipitation (Cámaro García and Dwyer, 2021).

- *Projected:* Projected changes in seasonal precipitation show marked shifts, with a 20% increase in the frequency of rapid high-intensity precipitation events during the autumn and winter months, mostly affecting the south and west coast of Ireland (Nolan and Flanagan, 2020). The number of 'wet days' (>20mm of daily precipitation) is expected to increase by 10% (RCP4.5) and 14% (RCP8.5), while the number of 'very wet days' (>30mm of daily precipitation) is expected to increase by 21% (RCP4.5) and 31% (RCP8.5), respectively (Nolan and Flanagan, 2020) (Figure 1). A substantial reduction in precipitation during the spring and summer months is projected, which will likely result in extended periods of water stress (Steele-Dunne *et al.,* 2008; EPA, 2020). Projections anticipate a 20% (RCP4.5) and 27% (RCP8.5) increase in the number of 'dry periods' (<1mm of precipitation daily, over a 5-day period) during the summer months, mostly affecting the east and southeast of the country (Nolan and Flanagan, 2020).

Hydrology:

- *Observed:* At a national level, river discharges are largely observed from 1972-2017, with shorter observations reported from 1992-2017 due to improved spatial coverage in hydrometric monitoring gauges (Cámaro García and Dwyer, 2021). Annual reduced river discharges, associated with increased low flow periods are evident in the east and south of the country from 1992 to present, while the midlands, west and north of Ireland largely show a pattern towards increasing flows (Cámaro García and Dwyer, 2021). A longer-term assessment reconstructed river flow in 51 Irish catchments from 1900-2016 was carried out by O'Connor *et al.* (2022). This research suggests an increasing trend is evident for annual, winter and autumn mean flows, particularly for catchments in the west and northwest (O'Connor *et al.* 2022). No significant trends were found for spring and summer mean flows from 1900 to 2016 (O'Connor *et al.,* 2022). A change in the direction of trends in the mid-1970s (particularly in annual and mean spring flows) may be driven by a switch to a predominantly positive phase of the North Atlantic Oscillation in the mid-1970s, which has been noted by Kiely (1999) and O'Connor *et al.* (2022). McCarthy *et al.* (2015) highlight the influence of the Atlantic Multidecadal Oscillation (AMO) on summer precipitation patterns; however, research is needed to investigate the influence of the AMO on summer river flows. The data across all observations indicate that river flows are increasing in the midlands, west and northwest of the country and decreasing in southern and eastern regions.

Although national groundwater levels are regularly monitored, the influence of climate change is not currently included in the monitoring parameters (Cámaro García and Dwyer, 2021).

- *Projected:* Projections suggest a more defined seasonality in the hydrological cycle, driven by changes in precipitation and temperature (Steele-Dunne *et al.,* 2014). Winter river flow is expected to increase by 20% by the mid to late century (Climate Ireland, 2022; Murphy and Charlton, 2007; Steele-Dunne *et al.,* 2014) (Figure 1.). O'Connor *et al.* (2022) suggest that projected climate change is likely to be associated with increases in winter flows, particularly for the west and northwest of Ireland, and potentially the midlands. The direction of change for summer river flows is uncertain according to O'Connor *et al.* (2022). However, the majority of future simulations suggest substantial decreases in mean summer flow by >40% across the country (Climate Ireland, 2022; Murphy and Charlton, 2007; Steele-Dunne *et al.,* 2014).
  Mean, 95th and 99th percentile annual groundwater flood levels in lowland karst are projected to increase by significant proportions for all future emission scenarios (Morrissey *et al.,* 2021). The frequency of extreme groundwater flooding events is predicted to increase, as well as a shift in seasonality of annual flooding, to later in the flooding season, with potential consequences for ecology and land use in the catchment (Morrissey *et al.,* 2021).

Sea Level Rise:

- *Observed:* Satellite observations indicate that sea level in Ireland has risen by 2-3mm per year since the early 1990s (Cámaro García and Dwyer, 2021). There is also a notable southeast to northwest gradient in rates of sea level rise due to local glacial isostatic adjustments. At Dublin port, the rate of sea level rise is estimated to be 6.9 cm from 1953 to 2016 (95% CI from 0.62 to 1.55 mm/yr), and 6.48 mm/yr during 1997-2016 (Nejad *et al.,* 2020). In Cork Harbour, the mean sea level has risen by 40 cm from 1842 to 2019, approximately in line with global mean sea level trends plus local glacial isostatic adjustment (Pugh *et al.,* 2021).

- *Projected:* Global sea levels are expected to increase between 0.43 m (0.29 to 0.59 m) and 0.84 m (0.61-1.10 m) for the RCP 4.5 and RCP 8.5 scenarios, respectively (Figure 1.). Irish projections for sea level rises are currently limited.

Waves and Storm Surge Events:

- *Observed:* Winter-mean wave height (vertical difference between the wave trough and crest), variability (marginal distributions of heights, lengths, and periods) and periodicity (time interval between consecutive wave crests or troughs) have increased from 1948-2017 in the northeast Atlantic (Castelle *et al.,* 2018). Winter wave heights have increased by up to 20 cm per decade, and a northward displacement of storm tracks is evident (Cámaro García and Dwyer, 2021).

- *Projected:* Increases in winter storm surge events along the Irish coastline will occur along the west and east coasts of Ireland (Wang *et al.,* 2008). Accurate projections for storm activity are limited.

Increased Carbon Dioxide (CO_2) in the Atmosphere and Ocean Acidification

- *Observed:* Long-term trends in atmospheric CO_2 recorded at Mace Head, Co. Galway show an increase of 2.22 ±0.04 ppm yr−1 between 2002-2018 (Nguyen *et al.,* 2022). Atmospheric CO_2 concentrations (413 ppm) recorded at Mace Head in 2018 were estimated to be >50% higher than those of the pre-industrial period (Cámaro García and Dwyer, 2021). Subsurface waters in the Rockall Trough, west of the Irish continental shelf, have decreased by 0.040 ±0.003 pH units between 1991 and 2010 (19-year period) (McGrath *et al.,* 2012). The labrador sea water in the Rockall Trough has acidified by 0.029 ±0.002 pH units between 1991 and 2010 (McGrath *et al.,* 2012). A reduction in calcite and aragonite saturation states was observed, which may have implications for calcifying organisms in the region.

- *Projected:* Globally, mean open-ocean surface pH is projected to decrease by 0.17 ±0.003 and 0.37 ±0.007 pH units for SSP2-4.5 and SSP5-8.5, respectively in 2081–2100 relative to 1995–2014 (IPCC, 2021, 2022). Surface ocean water is projected to be almost 150% more acidic by 2100 (Cámaro García and Dwyer, 2021). Ocean acidification is expected to drive large global economic impacts (*medium confidence*) (IPCC, 2022). Specific projections for Ireland including coastal and nearshore waters have yet to be generated.

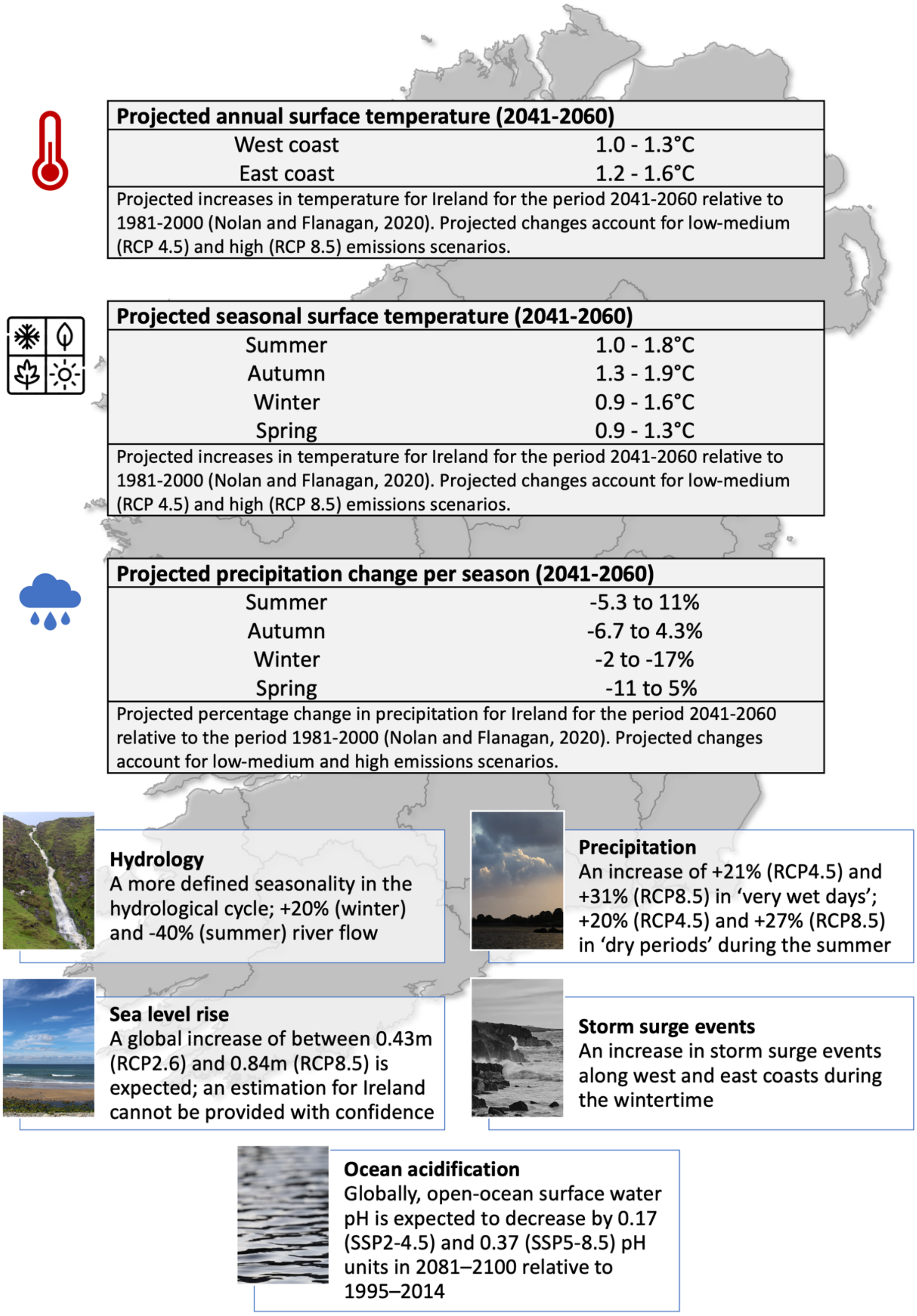


Figure 1. Infographic highlighting projected climate change for Ireland (Cámaro García and Dwyer, 2021; Climate Ireland, 2022; IPCC, 2021, 2022; Murphy and Charlton, 2007; Nolan and Flanagan, 2020; Steele-Dunne *et al.,* 2014; Wang *et al.,* 2008).

2. Water Quality and Anthropogenic Pressures

The quality of water affects biogeochemical processes and ecological dynamics that determine biodiversity, ecosystem productivity, and human health and welfare at local, regional, and national scales.

Surface waters are defined as any body of water that exists on the land surface. Ireland's surface water resources consist of approximately 12,000 lakes, at least 84,800 km of river or stream channels, hundreds of estuaries and over 14,000 km^2 of coastal waters (EPA, 2022a). Surface waters are both an important natural resource and are used by humans for domestic drinking water, wastewater treatment, irrigation, fisheries, industrial activities, hydropower generation, and recreational activities. Surface waters also support high levels of biodiversity in aquatic ecosystems and are a fundamental part of the biosphere.

Subsurface water (groundwater) exists in saturated areas below the land surface. Ireland has approximately 514 groundwater bodies ranging in size from 1-1,887 km^2 (EPA, 2022a). Groundwater is an important natural resource with 16% of the national population (~750,000 people) relying on private groundwater sources for daily domestic use (Andrade *et al.,* 2022). Groundwater is affected by changes in recharge patterns (distribution, amount and timing of precipitation, evapotranspiration losses and land cover) and land use (human activity).

The water quality of Ireland's lakes, rivers, estuaries and coastal waters has declined in the last five years (2016-2021) according to the recent EPA report on 'Water Quality in Ireland, 2016-2021' (EPA, 2022c). Agriculture is the most prevalent significant pressure impacting over 1,000 water bodies, followed by hydromorphology (453 water bodies impacted), forestry (232 water bodies impacted) and urban wastewater (214 water bodies impacted) (EPA, 2022c). Management of water pollution is complex, as contaminants can enter freshwater and marine systems from both point and diffuse sources. Point source refers to a single identifiable source of a substance and/or pollutant that enters the water body (Grill and Curtis, 2022); typically, they require discharge consent or a permit and are usually regularly monitored and quantified (Harrison *et al.,* 2019). Diffuse sources, as the term suggests, refer to the release of contaminants from multiple places and activities, with varying intensities (small to cumulative), surface areas (large to small) and timescales (short to long-term) (Grill and Curtis, 2022). Mobilisation of substances and/or pollutants from diffuse sources can be linked to rainfall events. From a monitoring and management perspective, unknown cumulative sources of diffuse pollution are most concerning (Carpenter *et al.,* 1998; Harrison *et al.,* 2019). The main pressures impacting water quality are:

i. Pollution of waterbodies by agricultural activities is the most significant pressure of environmental concern in Ireland (EPA, 2022c; Keegan *et al.,* 2014; Moss, 2008; Withers *et al.,* 2014). Direct and indirect inputs of organic matter, nutrients (nitrogen, phosphorus, ammonia) and herbicides and insecticides (i.e., cypermethrin) associated with agricultural activities are released into local water bodies, altering water geochemistry and natural freshwater ecosystems (Harrison *et al.,* 2019). Agriculture is a major source of nitrogenous gas emissions, such as ammonia (NH_3), nitric oxide (NO), and nitrous oxide (N_2O). Nitrogen deposition can enhance the effects of eutrophication, promote harmful cyanobacterial blooms, and increase water acidification (Kelleghan *et al.,* 2021; Pan *et al.,* 2022). Excessive livestock production and the use of synthetic fertilisers also contribute to a significant proportion of extra-regional sources of atmospheric pollution, which enter water bodies through wet deposition (gas combined with rainfall) (Luo *et al.,* 2022; Pan *et al.,* 2022). For example, synthetic fertilisers are used to increase crop yields; however, only 27.5-35% of the nitrogen applied is taken up by plants (Yu *et al.,* 2015), and the surplus is volatilized into the atmosphere (and also discharged into waterbodies) (Chen *et al.,* 2018). During periods of precipitation, wet deposition occurs, releasing extra-regional nutrients into surface water bodies (Luo *et al.,* 2022; Kelleghan *et al.,* 2021). Addressing diffuse agricultural sources of pollution remains a persistent problem (Boezeman *et al.,* 2020). The EPA recently reported that nutrient concentrations are in excess in 43% of rivers (mostly in the south and southeast of Ireland), with high nitrate concentrations, while nearly a third of rivers (30%) and lakes (33%) have elevated phosphorus concentrations (EPA, 2022c). Phosphorus levels are highest in lakes in the northeast of the country (EPA, 2022c). The excess in freshwater nutrient concentrations is affecting Ireland's marine environment through the increased outflow of nutrients from freshwater systems. In the last decade, the levels of nitrogen and phosphorus flowing into estuaries have increased by 20% and 37%, respectively (EPA, 2022c).

"Pollution of waterbodies by agricultural activities is the most significant pressure of environmental concern in Ireland."

(EPA, 2022c; Keegan *et al.,* 2014; Moss, 2008; Withers *et al.,* 2014).

i. A significant proportion of waterbodies are damaged by activities that alter their physical shape, flow and form (EPA, 2022c). These hydromorphological changes are driven by land drainage, navigational dredging, loss of connectivity of flood plains, along with the presence of barriers such as dams, weirs, and culverts in water systems. These notably affect aquatic habitats and ecosystem behaviour. The most recent EPA report on water quality in Ireland 2016-2021, states that over 400 surface water bodies are known to be affected by these modifications and activities (EPA, 2022c).

ii. **Forestry activities** such as planting, thinning and clear-felling can significantly impact water quality (EPA, 2022c). Forestry is also responsible for the release of nutrients (organic carbon, phosphorus and ammonium), acidic pollutants (leaching of metal cations), insecticides and herbicides (such as cypermethrin), and fine sediments (siltation) into freshwater sources, impacting water quality. These inputs can lead to a degradation of water quality, growth of algae blooms, acidification of water bodies and modified stream flow regimes (EPA, 2022a; Feeley *et al.,* 2013). Issues arise during periods of rapid, high-intensity precipitation events and flooding which mobilise nutrients, pollutants and sediments, and clear-felling activities significantly increase the runoff of substances (Palviainen *et al.,* 2015).

iii. **Urban wastewater** (municipal wastewater) is defined as contaminated rainwater runoff (stormwater) and wastewater released from domestic households and industrial activities (Speight, 2020). Urban wastewater often contains high levels of nitrogen, phosphorus, organic carbon, major ions, inorganic solids (such as silts), metals and metalloids (such as cadmium, lead, mercury), polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, perfluoro-octanyl sulphonic acids, pathogenic viruses, bacteria and protozoa (Aslibekian and Moles, 2003; Jones *et al.,* 2017; Lazur *et al.,* 2020; McGrory *et al.,* 2017; Prata *et al.,* 2018; Speight, 2020; Strungaru *et al.,* 2019). Emerging contaminants including perfluorooctanesulfonic acid (PFOS), polybrominated diphenyl ethers (PBDEs), microplastics and microfibers, toxic chemicals, pesticides, and pharmaceuticals can also be found in urban wastewater (Barbosa *et al.,* 2016; Lambert and Wagner, 2018; Nzangya *et al.,* 2021; Mellander and Jordan, 2021; Rosenfeld *et al.,* 2011). Some pesticides have been found in wastewater for decades (Cahill *et al.,* 2011). Issues arise during periods of rapid, high-intensity precipitation and flooding with leakages from broken and poorly managed or engineered systems (EPA, 2020). Combined sewage overflow is a significant problem in urban centres in Ireland, where infrastructure is older, as surface water runoff enters the sewer network and onwards to a wastewater treatment plant (Morgan *et al.,* 2017). All combined sewage overflow networks are designed with overflows into nearby waterbodies, to avoid sewers becoming overwhelmed in high rainfall events, and subsequent flooding in properties and public areas. The flows spilling from these systems is contaminated with sewage as well as pollutants from urban runoff. Greater storm intensity and prolonged precipitation events, along with a large housing density on the same sewage network, will likely lead to increased sewage overflow into urban rivers. However, most stormwater runoff is conveyed directly into aquatic environments (without treatment) through a separate piped network. The stormwater runoff can include chemicals deposited by vehicles, which include polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Goonetilleke and Lampard, 2019). This necessitates the need to for improved stormwater infrastructure (particularly in urban centres) that are designed to cope with more frequent and high magnitude precipitation events. Nature-based sustainable urban drainage systems should be explored to relieve flood water volume and improve water quality.

2.1 Current Status of Water Quality in Ireland

Water quality varies considerably between waterbodies (Figure 2.; EPA, 2022c). Water quality is declining across surface water bodies when compared to the EPA's last assessment that covered the period 2016-2021 (EPA, 2022c). Overall, there has been a 1% decline in river water bodies in satisfactory condition with 161 fish kills reported between 2016 and 2021 (EPA, 2022c). The number of monitored lakes, estuarine and coastal water bodies with satisfactory ecological conditions have declined by 2.7% (lakes), 15.7% (estuaries) and 9.5% (coastal) respectively, during the period of observation (EPA, 2022c). Fifty per cent of water bodies have failed to meet good chemical status (EPA, 2022c), which is mainly attributed to ubiquitous substances, such as polycyclic aromatic hydrocarbons and mercury (EPA, 2022c). Overall, 92% of groundwater bodies achieved a good chemical status for the period 2016-2021 (EPA, 2022c), however, a slight decline of 0.8% in the groundwater quality (now in poor condition) was recorded (EPA, 2022c).

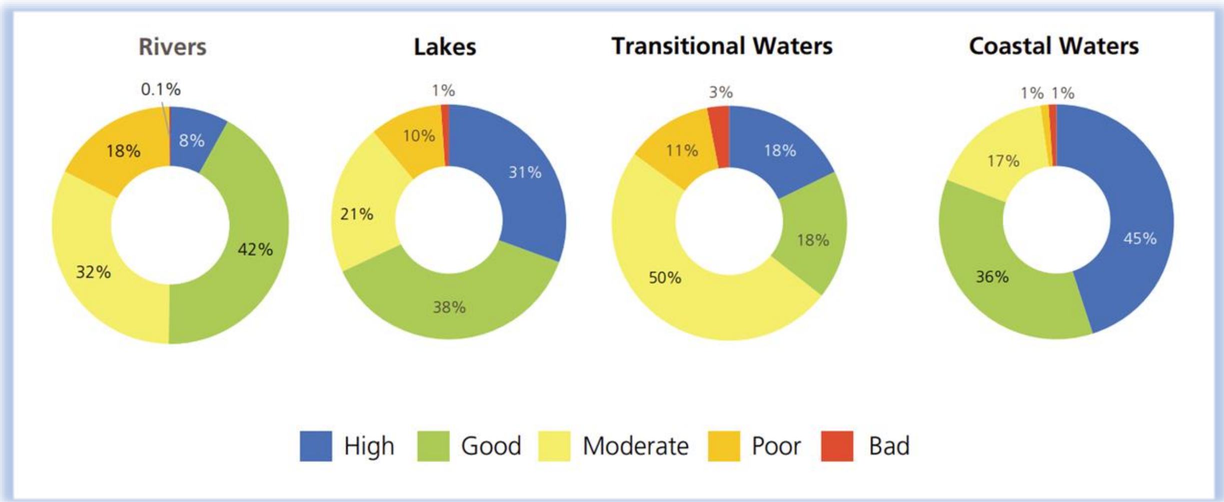


Figure 2. Proportion of surface water body categories in each ecological status class 2016-2018 (EPA, 2022c).

3. Impact of Climate Change on Water Quality

Climate change will likely exacerbate existing anthropogenic stressors, resulting in further degradation of water quality. According to the latest IPCC Climate Change 2022: Impacts, Adaptation and Vulnerability (2022) report, climate-induced decreases in water quality are acknowledged as an observed pressure with '*medium confidence'.* This is largely due to limited published evidence of global-scale changes in water quality, with many studies focusing on regional impacts. While research focusing on water quality is being conducted in an Irish context (Coffey *et al.,* 2016; McKeown and Potito 2016; Musacchio *et al.,* 2021; Smith *et al.,* 2012; Woolway *et al.,* 2019), there is a knowledge gap in research specifically focusing on the impacts of current and projected climate change on water quality in Ireland. This section will review the anticipated impacts of projected climate change on water quality and explores the following themes: i) elevated air and water temperature, ii) extended periods of low precipitation during the summer, iii) increased frequency of rapid high-intensity precipitation and flooding events, iv) the gradual rise in sea level and frequency of storm surge events, and v) other associated impacts such as increased carbon dioxide (CO_2) in the atmosphere.

3.1 Impacts Associated with Increased Air and Water Temperature

Increased air and water temperature will directly affect water quality and aquatic ecosystems physically, chemically, and biologically. These changes are discussed below in detail and are collated in Table 1.

3.1.1 Physical Changes

Increasing water temperatures have been documented globally in line with rising air temperatures (Woolway *et al.,* 2019). Shallow lakes and wetlands are particularly susceptible given their large surface-to-volume ratios (Feuchtmayr *et al.,* 2009). Annual minimum lake surface temperatures and have increased by approximately +0.35 °C per decade between 1973-2014 in Europe (Woolway *et al.,* 2019). Summer lake surface temperatures are increasing at an average rate of around +0.4 °C per decade, while oxygen concentrations are decreasing by 0.11 mg/l per decade (Copernicus, 2022). Climate change and a loss in water quality is contributing to deoxygenation of lakes temperate zones (Jane et al., 2021), with oxygen declines estimated to be between 2.75 to 9.3 times greater than observed in the world's oceans (Schmidtko *et al.,* 2017). The decline in surface water oxygen concentrations is largely attributed to reduced solubility of oxygen under warmer water conditions, while the decline in deep waters associated with stronger thermal stratification regimes and loss of water clarity, not with changes in gas solubility (Jane *et al*., 2021). Thus, warmer summer temperatures and extended summer stratification may increase the risk of dissolved oxygen depletion over greater areas and for longer periods of time. Longer stratification favours deep-water hypoxia and/or anoxia, which may enhance internal nutrient (i.e., phosphorus) release from bottom sediments (internal nutrient loading) by promoting manganese, nitrate, and iron reductions at the sediment-water interface (Tammeorg *et al.,* 2020). Under warmer conditions, the release of nutrients from internal sources could accelerate the eutrophication process, even if external nutrient sources are restrained (Anderson et al., 2002). Water quality policies for freshwater systems must consider synergies between legacy benthic nutrients and climate change. While increasing water temperatures due to climate change are frequently observed and the mechanisms for water temperatures interacting with legacy nutrients are well-established, the anticipated impacts of projected climate change on Irish lakes are not comprehensively understood and are limited to a small number of well-studied lakes, while time series frequency monitoring buoys are still generally too short (Marcé *et al.,* 2016). Coastal waters including the northwest European shelf are also affected by this warming trend, impacting seasonal stratification (Holt *et al.*, 2010).

3.1.2 Biological Changes

In surface and subsurface water bodies, increased water temperatures may exacerbate the effects of eutrophication. With increasing trophic state, the supply of organic matter increases (excessive growth of plants and algae due to the increased availability of photosynthetic growing factors) and hypolimnetic dissolved oxygen concentrations tend to decrease further, which may increase abundance of cyanobacterial blooms. A strong link exists between the dissolved oxygen in freshwater bodies and its thermal dynamics (as mentioned in section 3.1.1 above). At the simplest level, oxygen solubility decreases with rising temperature (Hutchinson, 1957), while increases in the duration of stratification (in lakes) can lengthen the period of isolation of hypolimnetic water from access to atmospheric oxygen (Moss et al. 2011). The effects of eutrophication will likely be worsened during the extreme warm years expected with climate change, as was observed during the heatwave in the summer of 2003 in Europe (Jankowski et al. 2006) and will have implications for species with narrow ecological ranges but may be beneficial to warm-water generalist fishes (Armstrong et al. 2021).

Cyanobacteria are photosynthetic bacteria naturally found in aquatic environments and rapidly grow in warm, nutrient-rich water (Codd *et al.,* 2005; Nazari-Sharabian *et al.,* 2018; Paerl and Scott, 2010).

This would put further pressures on surface water bodies as cyanobacteria can promote a reduction in dissolved oxygen content in the water (standing water bodies in particular), decrease light penetration and increase alkalinity of the water (Chislock *et al.,* 2013; Nazari-Sharabian *et al*., 2018). However, some cyanobacteria produce cyanotoxins (secondary metabolites), which threaten the safe use of water for drinking and recreational activities. These toxins can cause skin allergies and gastrointestinal disturbances (Levesque et al., 2014), along with acute liver (Zurawell *et al.,* 2005) and neurological disorders (Araoz *et al.,* 2010). Thus, an increase in cyanobacteria blooms may present a major risk to public health. Cyanobacterial toxicity is not limited to humans, it also affects many animals (Jean-François *et al.,* 2003) and has the potential to reduce the biodiversity of aquatic ecosystems (Svirčev *et al.,* 2014). Some cyanobacteria produce taste and odour compounds (Watson, 2003), which may require additional water treatment processes. Cylindrospermopsin (a cyanotoxin) has been detected in Irish rivers (Greer *et al.,* 2016) yet, to date, there are no official guidelines for cylindrospermopsin levels in drinking water in Europe. Increased temperature is a driving factor for cyanobacterial blooms in lakes, as it amplifies the onset, intensity, duration, and distribution of such blooms (Ahern *et al.,* 2006; Kosten *et al.,* 2012; Peeters *et al.,* 2007; Paul, 2008; Paerl and Huisman, 2008; Paerl *et al.,* 2011). Mitigating cyanobacterial blooms is and will continue to be, a major challenge for researchers and water managers with increasing temperatures exacerbating growth (Paerl *et al.,* 2016). In Ireland, cyanobacterial blooms are contaminating shellfish, which is impacting the viability of the shellfish industry (Sellner and Rensel, 2018). The Marine Institute provides weekly information on biotoxins and impacted shellfish for Irish coastal waters. Diarrhetic shellfish poisoning (DSP) and amnesic shellfish poisoning (ASP) are examples of the biotoxins being currently monitored (Marine Institute, 2022). The cost of monitoring toxins in saline coastal waters is expensive and substantially impacts turnover for the shellfish industries (Anderson *et al.,* 2000; Medlin, 2013). Overall, harmful cyanobacterial blooms threaten the quality of potable drinking water sources, biodiversity, fisheries and recreational activities (Chislock *et al.,* 2013; IPCC, 2022; Nazari-Sharabian *et al.,* 2018).

Native, cold-water aquatic species will be significantly affected by any increase in water temperature (Morato *et al.,* 2021; Morash *et al.,* 2021; Ruiz-Navarro *et al.,* 2016). Water temperature is an important environmental parameter for fish and macroinvertebrates, as temperature impacts most aspects of their physiology and ecology including reproduction, metabolic and developmental activities and mobility (Pletterbauer *et al.,* 2018). Non-optimal performance of these cold-water species, in combination with the presence of increased harmful cyanobacterial blooms and non-native invasive species (García *et al.,* 2005; Kernan, 2015) may threaten native freshwater and marine ecosystems in Ireland. For example, the Arctic charr (*Salvelinus alpinus L*.) a salmonid with a Holarctic distribution, is regarded as a 'sentinel' species for temperature-related climate change, as temperatures of 8.5 °C are adverse for high charr egg survival (Kelly *et al.,* 2020).

Warmer temperatures and altered hydrological patterns associated with climate change are expected to increase dissolved organic carbon (DOC) levels in water bodies. Increased temperatures stimulate microbial activities in organic matter decomposition and thus enhance dissolved organic carbon (DOC) production. DOC is derived from both aquatic (autochthonous) and terrestrial (allochthonous) vegetation sources, the latter being deposited and mobilised through streams (Antoniades, 2007; O'Driscoll *et al.,* 2018).

Warmer temperatures and climatic conditions can also influence the occurrence, stability, reproduction and mobilisation of pathogens including bacteria, viruses and parasites in water sources. Warmer temperatures have been shown to increase growth rates of noncholera *Vibrio* sp. in estuarine and coastal waters during summer months (Semenza *et al.,* 2012). Norovirus and *Cryptosporidium* are less temperature-sensitive and are more resilient than *Campylobacter* (Sterk *et al*., 2016) – more detail in Section 3.3.

3.1.3 Chemical Changes

Warmer temperatures will exacerbate disinfection by-product (DBPs) issues in drinking water, including the formation of carcinogenic Trihalomethanes (THMs). Chlorine disinfection of water is a common and relatively cheap way of eliminating waterborne diseases; however, the treatment process can produce undesirable disinfection by-products that have adverse effects on human health. THMs are a prominent issue for drinking water providers (Valdivia-Garcia *et al.,* 2019) due to their human health-related risks including increased rates of cancer and negative reproductive outcomes (Kolb *et al.,* 2017). THMs are formed during the chlorination of natural organic matter present in raw water sources. Increased organic matter and dissolved organic carbon (DOC) in Irish surface waters due to increased temperatures and modified precipitation patterns will likely pose a greater threat to the functioning and cost of water treatment processes for human consumption (Lu *et al.,* 2021; Naden *et al.,* 2010; Yang *et al.,* 2017). Furthermore, the rate of THM formation increases with temperature, humic acid concentration, pH and bromide ion concentration (O'Driscoll *et al.,* 2020; Valdivia-Garcia *et al.,* 2016), although the extent to which increased temperatures due to climate change will increase THM production and riverine dissolved organic content (DOC) export remains uncertain (O'Driscoll *et al.,* 2018) – more detail in Section 3.2.

Ireland has the highest reported THM exceedances in potable water across the European Union (EU) (O'Driscoll *et al.,* 2018). Fortunately, THMs typically do not persist in surface waters as they readily volatilize to the atmosphere and are, thus, not regulated pollutants in the aquatic environment. However, the increased export of organic matter and DOC from surface waters to water treatment plants will put pressure on these systems to remove THMs and other harmful by-products from the chlorination process. Possible implications of climate change for water management agencies may include a need for alternative treatment processes and optimisation or increased use of groundwater sources to maintain compliance with drinking water standards. In Europe, the legal limit for total THMs in drinking water is 100 µg L^{-1} (HSE, 2022). In 2018, 73 public water supplies and 24 group water schemes failed to comply with European standards and Ireland was issued with a letter of formal notice by the European Commission (EPA, 2021b). At the end of 2021, 19 supplies on the EPAs Remedial Action List were due to THM failures in water treatment facilities (EPA, 2022b). While the number of people affected by THM failures has decreased in 2021, the number of individual THM exceedances has increased (EPA, 2021).

Key Points

- Increased air and water temperature will directly and indirectly negatively affect surface water bodies (fresh and saline) physically, biologically, and chemically.
- Shallow lakes and wetlands will be particularly susceptible to increasing air and water temperature due to large surface-to-volume ratios.

Main Environmental Concerns

- **Altered thermal stratification** in lakes and coastal waters will affect dissolved oxygen levels, sediment suspension and changes in chemical properties, impacting water quality.
- Exacerbated effects of **eutrophication** and increased frequencies of **harmful cyanobacterial blooms** (reduced DO levels and light penetration and increased alkalinity of the water), aquatic organisms (biodiversity) and human health (aquaculture and recreational activities).
- Warmer temperatures stimulate microbial activities in organic matter decomposition and enhance DOC production. **Increased DOC export** will have implications for potable water with increased harmful chlorination by-products being produced, and the need for subsequent removal.
- **Loss of native cold-water species** due to altered thermal parameters and increased cyanobacterial blooms.
- Exacerbate disinfection by-product issues in drinking water, **(THMs)** with implications for human health and water treatment. The extent of this issue remains to be seen.

Table 1. Table indicating the specific environmental and ecological impacts of increased air and water temperature, and extended periods of abnormally low precipitation associated with climate change on water quality for each water body type.

Impact of Increased Air and Water Temperature, and Extended Periods of Abnormally Low Precipitation on Water Quality:										
Water Body	**Impact**									
Type	*Exacerbate Effects of Eutrophication*	*Harmful Cyanobacterial Blooms*	*Thermal stratification*	*Decreased DO*	*Waterborne Diseases*	*Increased DOC Export*	*Increased Invasive Species*	*Loss of Native Cold-Water Species*	*THM*	*Concentration of Contaminants (less dilution)*
Freshwater Lakes	✓	✓	✓	✓	✓	✓	✓	✓		✓
Rivers and Streams	✓	✓		✓	✓	✓	✓	✓		✓
Groundwater	✓	✓		✓	✓	✓			✓	✓
Transitional (estuaries) and Coastal Waters	✓	✓	✓	✓	✓	✓	✓	✓		✓
Peatlands	✓				✓	✓	✓		✓	✓
Treated Drinking Water	✓	✓	✓	✓	✓	✓			✓	✓
Legend: ✓= Yes, Grey Fill = Not Applicable										

3.2 Impacts Associated with Extended Periods of Abnormally Low Precipitation

Currently, there is no universally accepted definition for the term 'drought'; however, it is generally defined as an extended period of abnormally low precipitation (Lloyd-Hughes, 2014; Met Éireann 2022). Variability in nomenclature for 'drought' poses an issue in the scientific literature. Met Éireann alone provides three classifications for the term drought, 'agricultural', 'hydrological' and 'meteorological'. Under 'meteorological' there are three additional sub-classifications: i) 'A dry spell is a period of 15 or more consecutive days with less than 1 mm of rainfall.', ii) 'An absolute drought is a period of 15 or more consecutive days with less than 0.2 mm on each.' And iii) 'A partial drought is a period of at least 29 consecutive days with a rainfall total averaging less than 0.2 mm of rain per day.' (Met Éireann, 2022).

Under predicted climate change, Ireland will experience drier summer months with periods of abnormally low precipitation (Nolan and Flanagan, 2020). This is expected to be a significant issue for both water quality and quantity, in most surface waters and some subsurface waters (Steele-Dunne *et al.,* 2008) (Table 1.). The quality of water will be affected by the warmer temperature (section 3.1), evaporation rates altering water volume and subsequent concentration of contaminants (less dilution), therefore ultimately decreasing water quality (IPCC, 2022). Modified precipitation and infiltration patterns (runoff) in groundwater, may lead to less dilution of contaminants present in water, resulting in the concentration of pollutant levels above 'environmental quality standards' (EQS) for nitrates, phosphates, and emerging contaminants (Mellander and Jordan, 2021; Rosenfeld *et al.,* 2011). This concentrating effect of contaminants is expected to be a significant environmental issue. Increased concentrations of pollutants can exacerbate the effects of eutrophication, causing deoxygenation of the water by both lowering dissolved oxygen levels and increasing biochemical oxygen demand (BOD) within the water body (Nazari-Sharabian *et al*., 2018). Small rivers are particularly sensitive to changes in hydrology, where reduced volumes of water will amplify the effects of pollutants present in the water body (Pletterbauer *et al.,* 2018; Whitehead *et al.,* 2009; Weatherhead and Howden, 2009). In the short term, extended periods of abnormally low precipitation during the summer may temporarily reduce agricultural runoff into water bodies (Weatherhead and Howden, 2009). However, this will lead to a build-up of nutrients and contaminants in poorly managed soils and surfaces, which will eventually be released in higher concentrations through pulse events during periods of subsequent rapid high-intensity precipitation (Kaushal *et al.,* 2014; Qiu *et al.,* 2021; Van Metre *et al.,* 2016). Furthermore, inevitable increases in water usage during the summer months will place additional pressure on water sources, and issues for other wastewater releases during extended periods of low precipitation will likely arise (Hughes *et al.,* 2021).

Leaching of organic matter from soils is the key contributor to DOC in surface waters (Hejzlar et al., 2003) with 2.9 Pg C yr^{-1} reported to be mobilised (Regnier et al., 2013). Peatlands export more DOC than any other biome (Lugo et al., 1989). Increased DOC concentrations in stream waters from peat-covered catchments have increased over the last 15-25 years. Peatland drainage and lowering of water tables due to drier and warmer (increased evapotranspiration) conditions are associated with water quality impacts and export of DOC into drainage water and streams (Rothwell et al., 2010). Nieminen et al. (2021) indicated that total organic carbon (TOC) concentrations from drained peatland catchments were, on average, 8–14 mg l^{-1} higher than from undrained catchments in Finland and Sweden. In Ireland, climate warming and human impacts are thought to be causing peatlands to dry and potentially converting them from sinks to sources of carbon (Swindles et al. 2019).

Drinking water catchments in peatland regions will be particularly impacted due to increased dissolved organic matter concentrations being transported from peatlands to fluvial networks (Fenner and Freeman, 2011). It is anticipated that enhanced frequency and extended periods of abnormally low precipitation will increase DOC concentrations in Irish surface waters (Naden *et al.,* 2010). Concentrations of DOC in water from upland peatlands have increased rapidly in recent decades due to a combination of changes in atmospheric deposition chemistry and peat degradation (Evans *et al.,* 2005). The peatlands responsible for supplying high volumes of potable water in Ireland are all situated in upland areas (at least 300 m above sea level) (Xu *et al.,* 2018). Ireland consumes 0.19 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 4.22 million people in Ireland (Xu *et al.,* 2017). Projected climate change (warmer temperatures and modified precipitation) to 2100 is predicted to cause severe degradation of some peatlands (Li *et al.,* 2017), resulting in accelerated peat decomposition, release of aquatic carbon and reduction in peatland water quality (Fenner and Freeman, 2011). Thus, increasing the costs associated with disinfecting potable water in treatment plants to remove DOC and mitigate the production of harmful disinfection by-products during the chlorination process (O'Driscoll *et al.,* 2018; Li *et al.*, 2016; Ritson *et al.,* 2014).

Key Points

- Extended periods of abnormally low precipitation during summer months will be a significant issue for water quality.
- Most surface waters and some subsurface waters will be affected, particularly small streams.

Main Environmental Concerns

- Reduced precipitation may lead to **less dilution of contaminants** present in water, resulting in the concentration of pollutant levels above 'Environmental Quality Standards' (EQS) for nitrates, phosphates, and emerging contaminants.
- **Nutrients and contaminants will accumulate in poorly managed soils and surfaces during dry periods**, which could eventually be released in higher concentrations through pulse events and during periods of rapid high-intensity precipitation events.
- **Dissolved Organic Carbon (DOC) leaching** from peat soils, as a result of extended dry periods and warmer conditions, has implications for the quality of receiving waters, as well as the functioning and cost of water treatment processes for human consumption.
    - Enhanced DOC concentrations are a precursor for harmful disinfection by-products produced during chlorination, including potentially carcinogenic THMs.

3.3 Impacts Associated with Increased Frequency of Rapid High-Intensity Precipitation Events and Flooding

Increased frequency of rapid high-intensity precipitation events in the autumn and winter months is projected in Ireland (Table 2.). These events will exacerbate diffuse sources of pollution and impact water quality. Increased pollution runoff of nutrients, sediments, pathogens and other emerging contaminants from agricultural, urban wastewater, domestic and forestry sectors is expected. Rapid high-intensity precipitation events, after long periods of reduced precipitation, will be particularly harmful due to the accumulation of high concentrations of soluble contaminants in soils. Furthermore, rapid high-intensity precipitation events and subsequent peak flows may re-mobilise contaminants, that are contained within sediments in streams, rivers, and lakes. Rapid, high-intensity precipitation mobilises contaminants through pathways infiltrating all surface and groundwater systems (Geris *et al.,* 2022; Huebsch *et al.,* 2014). The effect will be amplified in areas lacking storm water infrastructure to treat urban runoff before discharging it into the environment (Willuweit et al. 2015). Shifts in precipitation patterns will have significant implications for combined sewage outflows (CSO) (Morgan *et al.,* 2017). Ordinarily in urban areas with a CSO, all the wastewater is treated before discharge; however, heavy rains can overwhelm the system, sending a cocktail of pathogens, active pharmaceutical ingredients, household chemicals, oil, pesticides, excess nutrients, and other pollutants straight into local receiving waters. In 2021, treatment at 12 of Ireland's 174 large urban areas failed to meet European Union standards and generated 49% of the total wastewater collected in all 174 large urban areas (EPA, 2022d). In 2019, the Court of Justice of the European Union ruled that collecting systems serving some areas were inadequate. Furthermore, there has been a 70% rise in the breakdown of equipment at waste water treatment plants between 2019-2021, with around 330 breakdowns in 2021 (EPA, 2022d). The combination of CSOs, failing infrastructure and climate change will increase pressure to maintain or improve water quality standards, along with compliance under the Water Framework Directive. Uisce Éireann's (Irish Water) next investment plan will run from 2025 to 2029 (EPA, 2022d). It is crucial that these plans incorporate climate change projections (regional rainfall patterns) to improve and prioritise future stormwater capacity in CSO wastewater treatment plants. Alternatively, separating stormwater and municipal wastewater would alleviate pollution during heavy rains. Stormwater still needs a level of treatment to remove contaminants (heavy metals and hydrocarbons etc) and could be diverted into treatment areas before discharge into receiving surface water or groundwater systems. Such treatment areas that are growing in popularity include constructed wetlands, raingardens, and swales – referred to as Sustainable Drainage Systems (SuDS). This would have the dual benefit of slowing down (attenuating) and treating water during high intensity and/or duration precipitation events.

Abrupt changes in precipitation can impact groundwater quality (Geris *et al.,* 2022), particularly in climate-sensitive karst regions (Stevanović and Stevanović, 2021). Karst groundwater behaves similarly to surface bodies, with rapid flow paths through karstic conduit systems where water tables fluctuate seasonally between 10-20 m. In these areas, thin soils afford little opportunity for attenuation in micro-porous media; hence, contaminant infiltration can easily take place during flow events. However, contaminant export depends on the mass of pollutants stored on the surface prior to the rapid, high-intensity precipitation event and the subsurface flow pathways (Huebsch *et al.,* 2014). In Ireland, nitrates, trace elements (metals and metalloids such as arsenic), and pesticides, are the common pollutants in groundwater causing a significant concern and health threat to consumers (Baily *et al.,* 2011; McGrory *et al.,* 2017; McManus *et al.,* 2017; Tedd *et al.,* 2014). To note, the discharge of contaminants (i.e., the quantity or mass flux) from industries and land use will remain the same unless expansion of this sector occurs in the future; however, the mobilisation of these contaminants will change with modified precipitation patterns. Groundwater systems are complex in nature and require knowledge of the interactions between recharge, storage, and transport processes for each system (Naughton *et al.,* 2017). Management and forecasting for groundwater systems in response to climate change will prove difficult for management agencies as adequate data (mapping) is currently absent (Naughton *et al.,* 2017). Whilst karst regions are the most sensitive to the impacts of climate change (O'Driscoll *et al.,* 2020; Pavlis and Cummins, 2014), areas of sand and gravel and Quaternary deposits in the east and midlands, are more resilient due to a large storage capacity with slow flow rates and filtration and therefore will be less affected by any extremes in climate. Thus, groundwater in Karst regions to the west of Ireland, which are expected to receive higher rainfall, could be more susceptible to deterioration in water quality with future climate change.

Table 2. Table indicating the specific environmental and ecological impacts of increased frequency of rapid high-intensity precipitation events and flooding associated with climate change on water quality for each water body type.

Impact of Heavy Precipitation Events and Flooding on Water Quality			
Water Bodies	**Impacts**		
Type	*Increased Contaminant Mobilisation*	*Mobilisation of Waterborne Diseases*	*Atmospheric Wet Deposition of Nutrients*
Freshwater Lakes	✓	✓	✓
Rivers and Streams	✓	✓	✓
Groundwater	✓	✓	✓
Transitional (estuaries) and Coastal Waters	✓	✓	✓
Peatlands	✓	?	✓
Legend: ✓= Yes; ? = Unknown			

The concentration of pathogens in surface water increases after extreme precipitation events due to increased surface runoff, sewer overflow and re-suspension from sediments (Funari *et al.,* 2012; Hofstra, 2011). Outbreaks of waterborne diseases generally occur after flooding events due to contaminated surface water and disrupted sewage-disposal systems (Qadri et al., 2005). Simultaneously, increased precipitation decreases the concentration of pollutants in surface water due to dilution (Hofstra, 2011). Increased winter rainfall will cause significant impacts on microbial transport, representing a period of increased risk to both drinking water and bathing waters. An increase in microbial source loads on land, concomitantly with projected changes in climate is likely to exert greater microbial pollutant pressures on surface waters (Coffey et al., 2016). Andrade et al. (2022) show a 5-day and 30-day antecedent rainfall increased the likelihood of *E. coli* contamination. However, O'Dwyer *et al*. (2021) found *E. coli* present in groundwater sites in the southwest of Ireland during extended periods of low precipitation during the summer and post-drought sampling periods, which the authors state is unexpected due to the lack of microbial transport. This suggests that there may be some level of bacterial adaptation in the sub-surface (Dwyer et al., 2021). Human exposure to waterborne pathogens may differ substantially from the current pattern due to the impact of climate change (Islam et al., 2021). However, the relative influence of climatic factors on pathogen concentrations remains poorly understood (Vermeulen and Hofstra, 2013). The increased prevalence of waterborne diseases will put additional pressure on water treatment plants and incur issues with increased production of chlorination by-products and subsequent removal (Valdivia-Garcia et al., 2016). Furthermore, climate change is expected to influence infection risks in bathing water downstream from intensive agricultural land, combined sewage overflows (CSO) systems and waste water treatment plants (Sterk *et al*., 2016; Boxall *et al*., 2009). Sterk *et al*. (2016) argue that a decrease in dilution capacity of sewage in surface waters could have a significant impact on the infection risks of relatively stable pathogens such as *Cryptosporidium* and norovirus.

Key Points

- Increased frequency and intensity of rapid, high-intensity precipitation events during the autumn and winter months will mobilise contaminants, sediments and waterborne pathogens.
- Water quality of surface and subsurface water bodies will be affected, particularly groundwater in vulnerable climate-sensitive karst regions.

Main Environmental Concerns

- Rapid, high-intensity precipitation events, after extended dry periods, will be particularly harmful due to the **accumulation of high concentrations of soluble contaminants in soils and subsequent remobilisation to water courses**.
- Heavy rains can **overwhelm combined sewerage overflow systems**, sending a cocktail of pathogens, active pharmaceutical ingredients, household chemicals, oil, pesticides, nutrients, organic waste and other pollutants straight into local receiving waters.
- **Re-mobilisation of contaminants** contained within sediments in streams, rivers, and lakes.
- Increased **prevalence of pathogens** in surface water due to increased surface runoff, sewer overflow and re-suspension from sediment. Implications for human health and water treatment plants.

3.4 Impacts Associated with Gradual Sea Level Rise and Storm Surge Events

Saline intrusion of coastal aquifers and estuaries is expected with the gradual rise in sea level and the increased frequency of storm surge events (the abnormal rise of water above the high tide mark generated by low-pressure weather system) (Moore and Joy, 2021). Saline intrusion will compromise drinking water quality by increasing total dissolved solids concentrations, altering the biogeochemistry of the aquifers and increasing corrosion of buried infrastructure (Kolb *et al.,* 2017; Moore and Joy, 2021). In freshwater coastal aquifers, saline intrusion can change the ionic strength and oxidation of carbon (through sulphate-reducing bacteria), resulting in enrichment in dissolved macro- and micro-nutrients, inorganic and organic carbon, sulphide, metals, radiative gases and radionuclide tracers (Moore and Joy, 2021). In coastal areas where groundwater is extracted for use, lowering of water tables can cause marine water ingress into the groundwater system, and landward migration of the saline-freshwater interface if not carefully managed. While only a small proportion of Ireland's coastal aquifers are exploited for potable water, almost half of all registered Irish hotels and B&Bs are located within five kilometres of the coastline (Fáilte Ireland, 2018). Saline intrusion in coastal aquifers would limit the potential to tap into groundwater reserves in the future for the tourism industry.

Finally, expected increases in storm frequency and associated higher wind speeds will accelerate sediment resuspension, contaminant circulation, and exacerbate the effects of eutrophication, particularly in large shallow systems such as freshwater lakes. However, intense and high-speed winds can also obstruct the growth of algal blooms in surface waters by dissipating them and weakening their formation temporarily (Nazari-Sharabian *et al.,* 2018).

Key Points

- A gradual rise in sea level and an increased frequency of storm surge events are expected to cause saline intrusion compromising coastal aquifers as drinking water sources.

Main Environmental Concerns

- Saline intrusion will compromise drinking water quality by **increasing total dissolved solids (TDS)** concentrations, altering the biogeochemistry of the aquifers and increased corrosion of buried infrastructure, with implications for water treatment.

3.5 Other Associated Impacts

Carbon dioxide (CO_2) present in the atmosphere, naturally dissolves into fresh and marine water bodies. The burning of fossil fuels has led to increased CO_2 in the atmosphere and subsequently, more CO_2 is being dissolved. Water and CO_2 combine to form a weak carbonic acid (H_2CO_3), which causes acidification and results in a decrease in water pH. Ocean and freshwater acidification not only affects water quality, but also have serious consequences for food webs, the physiology of aquatic organisms, biodiversity, and the mobility of many metals and metalloids (Arneth *et al.,* 2020; Bednaršek *et al.,* 2019; Davis *et al.,* 2007; Doney *et al.,* 2020) (Table 3.). Lower pH levels will contribute to the solubilisation of sediments and contaminants, including trace elements (aluminium, lead, copper and cadmium) impacting water quality with implications for aquatic organisms, human health and drinking water management (Millerno *et al.,* 2009; Peng *et al.,* 2009).

Key Points

- Increased dissolution of anthropogenic carbon dioxide (CO_2) from the atmosphere in surface waters causes **ocean and freshwater acidification**.

Main Environmental Concerns

- Lower pH levels will **alter water geochemistry** and threaten food webs, the physiology of aquatic organisms and biodiversity
- Lower pH levels will contribute to the **solubilisation of sediments and contaminants including trace elements** (aluminium, lead, copper and cadmium) impacting water quality. Implications for aquatic organisms, human health and drinking water management.

Table 3. Table indicating the specific environmental impacts of other associated climate change impacts on water quality for each water body type.

Other Associated Climate Change Impacts on Water Quality					
Water Bodies	**Sea Level Rise and Storm Surge Events**		**Increased CO_2**	**Wind**	
Type	Saline Intrusion Increasing TDS Concentrations	THM	Acidification	Contaminant Circulation	Sediment Resuspension
Freshwater Lakes			✓	✓	✓
Rivers and Streams			✓	✓	
Groundwater	✓	✓	✓		
Transitional (estuaries) and Coastal Waters			✓	✓	✓
Coastal Peatlands	✓	?	✓	✓	
Treated Drinking Water	✓	✓			
Legend: ✓= Yes; ? = Unknown; Grey Fill = Not Applicable TDS = Total Dissolved Concentrations					

To conclude, climate change and associated weather dynamics will exacerbate anthropogenic pressures that are already affecting water quality in Ireland. Significant impacts are expected resulting in i) further degradation of aquatic ecosystem health and ii) contamination and alteration of natural water geochemistry impacting its usability for drinking water sources.

4. Legislation and Policy in Ireland

This section of the report reviews the foundational structure of the current European and Irish legislation and national policies documents and adaptation plans. The identified impacts outlined in the previous section were used to structure and inform this review. Relevant directives and policies were reviewed individually and as a whole to explore alignment and possible discrepancies.

A 'directive' is a legislative act that sets out a goal that all EU countries must achieve.

The following EU directives are relevant for mitigating sources of pollution and subsequent protection and restoration of water quality.

National Plans consist of principles and a broad course of action adopted by the national government in pursuit of a specific objective.

The following relevant EU legislation and Irish national plans were reviewed in the context of water quality and climate change (Table 4.).

Table 4. A full list of EU legislations and national plans that were reviewed for this report.

Legislation and Polices Reviewed
EU Legislation
Water Framework Directive (A framework for Community action in the field of water policy - 2000/60/EC)
Floods Directive (Assessment and management of flood risks - 2007/60/EC)
Habitats Directive (Conservation of natural habitats and of wild fauna and flora - 92/43/EEC)
Environmental Quality Standards Directive (in the field of water policy - 2008/105/EC)
Industrial Emissions Directive (integrated pollution prevention and control - 2010/75/EU)
Bathing Water Directive (Management of bathing water quality - 2006/7/EC)
Groundwater Directive (Protection of groundwater against pollution and deterioration - 2006/118/EC)
Nitrates Directive (Protection of waters against pollution caused by nitrates from agricultural sources - 91/676/EEC)
Drinking Water Directive (Quality of water intended for human consumption - EU 2020/2184)
Urban Waste Water Treatment Directive (91/271/EEC)
National Plans
Biodiversity Action Plan (Draft, fourth cycle)
Climate Action Plan 2021
Climate Change Sectoral Adaptation Plans for the following sectors: • Agriculture, Forest and Seafood • Biodiversity

• Built and Archaeological Heritage • Communication Networks • Electricity and Gas Networks • Flood Risk Management • Health • Transport • **Water Quality and Water Services**
National Development Plan 2021 – 2030
National Water Resources Plan – Framework Plan 2021 (Uisce Éireann: Irish Water)
Nitrates Action Plan 2022
River Basin Management Plan 2022 – 2027 (3rd cycle draft)
Water Services Policy Statement 2018-2025

4.1 Key Findings and Recommendations

4.1.1 Recognition of Climate Change in the EU Legislation

Since the 1990s, governments have collectively pledged to slow anthropogenic climate change. In 1992, the United National Framework on Climate Change (UCFCCC) was the first global treaty to explicitly address climate change. The Treaty established an annual forum known as the Conference of Parties (COP) for international discussions aimed at stabilising the concentration of greenhouse gases in the atmosphere. These meetings produced the Kyoto Protocol (adopted in 1997 and entered into force in 2005) and the Paris Agreement (2015). The Kyoto Protocol was the first legally binding climate treaty; however, the treaty did not compel developed nations and large greenhouse gas-emitting countries to act. The most significant global climate agreement to date, the Paris Agreement, requires all countries to set emissions-reduction pledges. Governments set targets, known as nationally determined contributions, with the goal of preventing the global average temperature from rising above 2°C above pre-industrial levels and pursuing efforts to keep temperature below 1.5°C. The Paris Agreement aims to reach net-zero emissions in the second half of the century. EU legislation is slowly addressing climate change and the various EU directives (relating to water) are mapped on a timeline with international climate agreements in Figure 3.

Figure 3. Timeline for International Policies and Agreements.

- **Finding 1:** Only two of the ten EU directives listed above acknowledge climate change as a variable (Table 5.). These directives provide the foundation for national policies as a legislative act that sets out a goal that all EU countries must achieve (e.g. the Nitrates Directive has been transposed into Irish law, via the Nitrates Action Plan). Figure 4 illustrates the hierarchical structure of EU policies and Irish national governance bodies and plans for both climate change and freshwater issues. There is clear misalignment in EU legislation and national policies and plans. Many of the EU directives in use today were published in the 1990's and early 2000's. Despite European commitments under the UNFCCC and Kyoto Protocol, there has been a lack of integration of the impacts of climate change on the water sector at the policy level. Scientific knowledge has greatly advanced since the compilation of many of these EU directives, particularly relating to the *Protection of waters against pollution caused by nitrates from agricultural sources* directive (91/676/EEC), the *Urban Waste Water Treatment* directive (91/271/EEC), the *Conservation of natural habitats and of wild fauna and flora* directive (92/43/EEC), and the framework for community action in the field of water policy (Directive 2000/60/EC). Thus, highlighting the urgent need for revision of EU legislation to recognise and include the impact of climate change on water quality and aquatic ecosystems. **To deal effectively with the impacts of climate change and associated weather dynamics, amendments need to be made to EU legislation.**

  The *Fit for 55* package as part of the European Commission's Green Deal, aims to generate new and revised legislation in response to this issue. The legislative proposal, to be accompanied by an impact assessment, for the revision of the *Urban Waste Water Treatment* directive was expected in the second quarter of 2022. According to the provisional agenda of the College of Commissioners for the second half of the year, it is currently planned for the end of October 2022 (European Parliament, 2022). The revision of EU legislation and subsequent Irish legislation should be prioritised and expedited. The current draft of the *River Basin Management Plan 2022 - 2027*, also acknowledges this issue, highlighting the need for revision of EU Directives.

» ***Recommendation 1:*** In the *Urban Waste Water Treatment* directive, Annex 1 "*extreme values for the water quality in question shall not be taken into consideration when they are the result of unusual situations such as those due to heavy rain*". Climate change projections include increased frequency and intensity of rapid, high-intensity precipitation events and flooding for Ireland and the EU, therefore '*heavy rain*' will no longer be an '*unusual event*', highlighting the necessity to revise this directive.

» ***Recommendation 2:*** Additionally, in the *Urban Waste Water Treatment* directive, Annex II, "*a marine water body*" is considered a "*less sensitive area*". The recent EPA report on Water Quality in Ireland shows a significant decline in transitional (estuarine) and coastal waters, which indicates that they are sensitive areas.

» ***Recommendation 3:*** Warmer water temperature associated with climate change will exacerbate the formation of harmful cyanobacterial blooms in standing waters. This factor should be included in the *Management of bathing water quality* directive (2006/7/EC), Annex III bathing water profile.

Recommendation 4: The *Protection of waters against pollution caused by nitrates from agricultural sources* (Nitrates) directive (91/676/EEC) does not consider surplus nitrogen pollution, which is volatilised into the atmosphere from chemical fertiliser application. Atmospheric nitrogen deposition is a significant extra-regional nutrient source through wet deposition; the exclusion of this process is a fundamental oversight. The lack of inclusion of climate change as an influencing variable on various water-related directives is highlighted in Table 5.

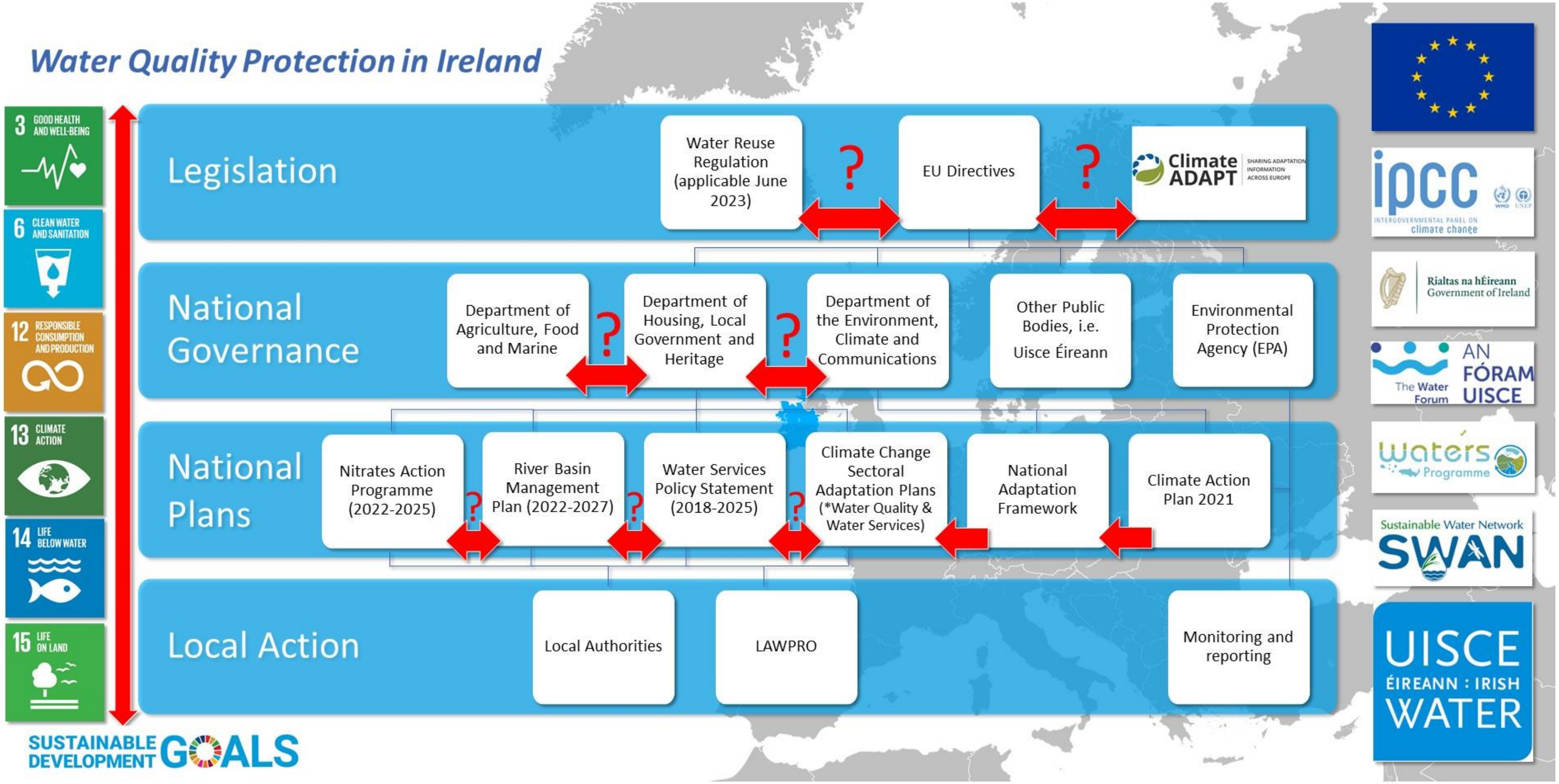


Figure 4. A graphical representation of the network of stakeholders for water quality in Ireland. The hierarchal graphic highlights misalignment and discrepancies (in red) between bodies which seek to improve and protect water quality when reviewed holistically. Legend: * = the Water Quality and Water Services, Climate Change Sectoral Adaptation Plan is the most relevant of the nine plans, cross-sectoral linkages are present with these plans. Water Quality is addressed in The 2030 Agenda and Sustainable Development Goals (SDGs) and is recognised in goals 3, 6, 12, 13, 14, 15.

Table 5. A list of EU Directives indicating the inclusion of 'climate change' as a driver for water quality degradation.

The Inclusion of Climate Change in EU Legislation Highlighting the need for Revision	
EU Legislation	**Inclusion**
Bathing Water Directive 2006/7/EC	**No**
Habitats Directive 92/43/EEC	**No**
Drinking Water Directive EU 2020/2184	**Yes**
Environmental Quality Standards Directive 2008/105/EC	**No**
Floods Directive 2007/60/EC	**Yes**
Groundwater Directive 2006/118/EC	**No**
Nitrates 91/676/EEC	**No**
Urban Waste Water Treatment Directive 91/271/EEC	**No**
Water Framework Directive 2000/60/EC	**No**
Industrial Emissions Directive 2010/75/EU	**No**

4.1.2 Alignment of Climate Change and Water Quality Policies and Present Discrepancies

An integrated approach is lacking for current national policies, resulting in misalignment and underrepresentation of forthcoming climate-related impacts on water quality. Figure 5. illustrates the timeline of national climate and water quality plans and acts in Ireland. The following discrepancies were identified for each policy in this section.

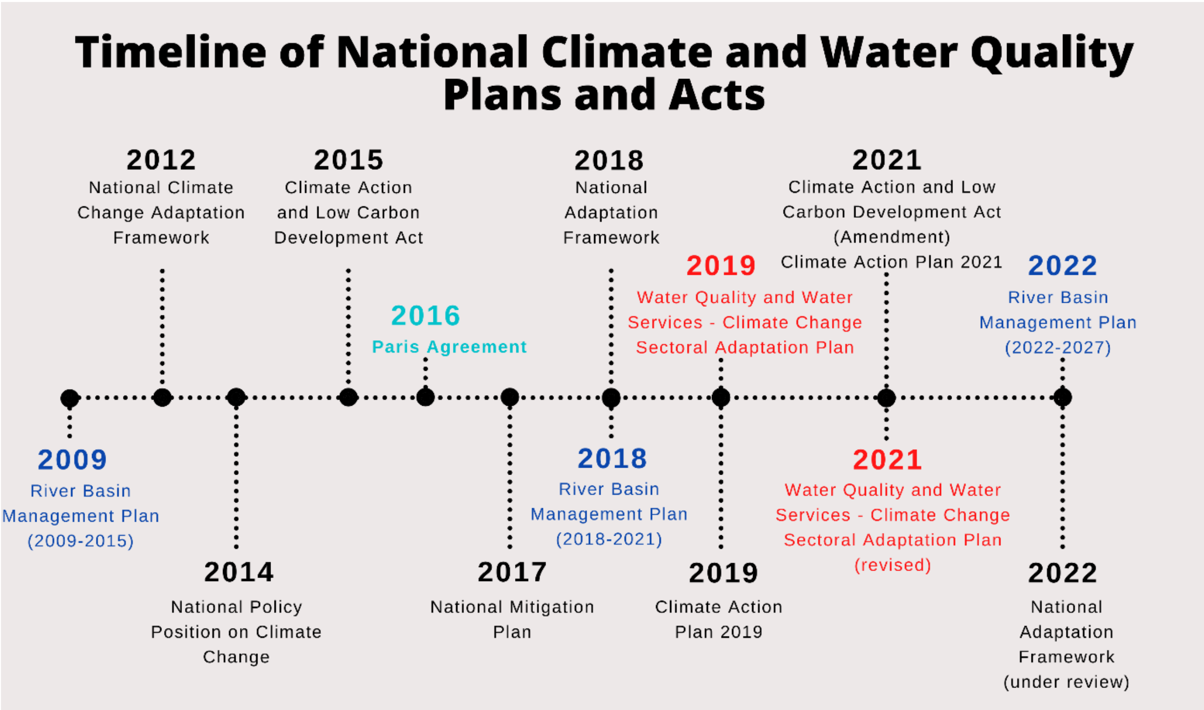


Figure 5. Timeline of National Policies Relating to Climate and Water Quality in Ireland.

1) River Basin Management Plan 2022-2027 – Review

The draft *River Basin Management Plan 2022-2027* (third cycle) prepared by the Department of Housing, Local Government and Heritage, Government of Ireland, was published in September 2021 and last updated in June 2022. This plan also exhibits a **misalignment with other relevant policies, regarding the interlinking processes and breadth of impact** expected from climate change – see Section 5.0 Table 13.

- **Finding 1:** The impacts of climate change on water quality are underrepresented and do not adequately plan for expected changes for rivers and streams. Section 3.4 *Impacts of Climate Change* is limited to i) high rainfall and flooding leading to mobilisation of pollutants, ii) reduced dilution of contaminants in water bodies at low flow, iii) drying of peatland resulting in the reduction of natural filtration of pollutants, iv) increased spread and viability of pathogens, such as livestock waste and slurry and v) changes in the distribution and viability of native, non-native and invasive flora and fauna. These are the summarised main challenges that are also outlined in the *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan* and are not a comprehensive inventory of expected impacts. **The following main environmental impacts should be included:**

  - ***Recommendation 1:*** Exacerbated effects of eutrophication and the presence of cyanobacterial harmful algae blooms relating to warmer temperatures and modified precipitation. This will have implications for water quality (reduced dissolved oxygen levels, light penetration and increased alkalinity of the water), aquatic organisms (biodiversity) and human health (aquaculture and recreational activities).

  - ***Recommendation 2:*** A deeper understanding of anticipated impacts of dissolved organic carbon (DOC) from organic soils and peatlands due to climate change will impact water bodies and resulting contaminant mitigation in drinking water treatment. DOC export is currently not regulated in Irish surface waters and will likely pose a significant issue to the functioning and cost of water treatment processes for human consumption.

  - ***Recommendation 3:*** The influence of atmospheric wet deposition of nutrients e.g. nitrogen and ammonium and subsequent enrichment should be included. The increased nutrient influx will exacerbate the effects of eutrophication and the prevalence of harmful cyanobacterial blooms, amongst other aquatic ecosystem alterations impacting water quality and restoration plans of water bodies.

  - See Section 5.0, Table 13. for a full list of discrepancies.

- **Finding 2:** For the most part, this plan **separates the expected impacts of climate change from human-related pollution as exclusive pressures on water quality**, with the exception of ‘urban runoff pressures’. Climate change is exacerbating existing human-induced pollution altering natural water geochemistry and, ultimately, leading to further degradation of water quality and aquatic ecosystems.

» ***Recommendation:*** The impacts of climate change on water quality should not be addressed in isolation. Both drivers of water quality degradation should be addressed in tandem to adequately mitigate environmental impact, similar to 'urban runoff pressures'.

- **Finding 3: Policy actions include revisions of other plans as viable actions**. The *River Basin Management Plan 2022-2027* also seeks to '*update the Climate Adaptation Plan for the Water Quality and Water Infrastructure Sectors*', despite being more comprehensive in terms of the impact of climate change on water quality (Table 6.). Actions outlined need to be more targeted, measurable, and ambitious. Additionally, the *Climate Action Plan 2021* seeks to '*publish a new and strengthened River Basin Management Plan for the period 2022-2027*'.

Table 6. A list of relevant actions for water quality outlined in the *River Basin Management Plan 2018-2027*. Bold text highlighting the early stage of progression and revision of more comprehensive plans as viable actions.

RBMP 2022-2027 – Actions for Impacts of Climate Change	
1	To ensure that the actions selected are effective, sustainable and cost efficient under changing conditions, a 'climate check' will be required for all measures carried out under this plan.
2	**Update the Climate Adaptation Plan for the water quality and water infrastructure sectors.**
3	Examine opportunities in the monitoring programmes to **improve our understanding** of climate change trends.
4	**Support additional research and pilot projects** in the area of climate change.

» ***Recommendation:*** Officials within government departments should seek to communicate and collaborate on reports to produce a more cost-effective and holistic plan that are complementary. Individuals responsible for consulting on the *River Basin Management Plan 2022-2027* should consult with staff members responsible for producing the *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan*, along with specialist academics in HEIs. Inadequate public participation measures are also evident in the plan and there is a need for more active participation earlier in plan formulation.

2) Climate Action Plan 2021 – Review

The *Climate Action Plan 2021* is the main climate change adaptation framework for Ireland, compiled by the Department of the Environment, Climate and Communications, Government of Ireland and published in November 2021 and revised in June 2022. The plan outlines the roadmap for reducing our greenhouse gas emissions and management of associated human activities. The *Climate Action Plan* sets out actions across the different government sectors. Included in the *Climate Action Plan 2021* are climate adaptation measures that build upon the National Adaptation Framework (NAF). There are nine Climate Change Sectoral Adaptation Plans, which will be discussed in section 3 and 4 below.

The overview of the Climate Action Plan is discussed below in isolation from the sectoral adaptation plans.

- **Finding 1:** The impact of climate change on water quality is notably underrepresented, particularly in Chapter 21 *Adaptation* of the current plan. This chapter exclusively identifies the following water quality-related aspects as potential impacts of climate change**:** i) '*projected increases in the frequency of extreme precipitation events may result in more water-borne disease (e.g. E. coli) from contamination of drinking water as a result of overland flows of pollutants*', and ii) '*projected increases in the frequency of extreme precipitation events will result in increased levels of run-off and potential water quality issues, with implications for slurry storage and land spreading*'.

    » ***Recommendation:*** The impacts listed in Box 21.1, Page 202 – *Potential Impacts of Climate Change in Ireland*, require a significant revision to provide an informed and comprehensive review. Impacts should be identified as 'expected' not 'potential' impacts.

- **Finding 2:** The *Climate Action Plan 2021* includes alignment with Sustainable Development Goals (SDGs) in Chapter 20, again misalignment is evident regarding water quality and biodiversity issues with current and projected climate change. *Life Below Water* SDG (14) is referred to as a related goal of less importance and only refers to target 14.1 *reducing marine pollution*.

    » ***Recommendation 1:*** Other relevant and highly important SDG targets such as 14.3 *ocean acidification*, 14.2 *protect and restore ecosystems*, 14.5 *conserve coastal and marine areas* and 14.8 *increase scientific knowledge, research and technology for ocean health* should also be included.

    » ***Recommendation 2:*** The *Life On Land* SDG (15) should also include the following relevant targets, 15.5 *Protect Biodiversity and Natural Habitats*, 15.8 *Prevent invasive alien species on land and in water ecosystems*, and 15.9 *Integrate ecosystem and biodiversity in governmental planning*.

    » Various other SDGs relate to the anticipated impacts of water quality from current and projected climate change, including SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production).

- **Finding 3:** In a final observation, the outlined actions to mitigate the impacts of climate change on water quality highlight the plan's early stage of progression, with the majority of actions pertaining to *developing* or *exploring* related schemes or actions (Table 7.). These actions need to be significantly expedited, and more ambitious with clear measurable targets, to meet European and national climate change and water quality objectives.

Table 7. A list of relevant actions for water quality in the *Climate Action Plan 2021*. Bold text highlighting the early stage of progression.

Climate Action Plan 2021 – Actions Relevant to Water Quality	
No.	**Action**
323	Establish a centre for excellence for innovation in climate smart agriculture and land-use for the agri-food sector.
439	Assess appropriate adaptation measures for those existing flood relief schemes, where climate change may in time impact the current standard of protection.
440	Undertake a Scheme Adaptation Plan during the detailed development of new flood relief schemes, setting out how climate change has been taken into account during the design and construction, and what adaptation measures might be needed into the future.
444	Build on Groundwater Flood Mapping delivered by GSI.
445	Expand the groundwater monitoring network for analysis of climate change effects.
452	Publish a new and strengthened River Basin Management Plan for the period 2022-2027.
453	Explore options for the delivery of a National Implementation Strategy for nature-based sustainable urban drainage systems.
454	Develop interim guidance on best practice on nature-based sustainable urban drainage systems.
455	Review of the Sectoral Adaptation Plan for the Water Quality and Water Services Infrastructure sectors.
456	Adopt the four regional plans under Uisce Éireann's National Water Resources Framework Plan.
459	Develop a better understanding of the health impacts of climate change in Ireland.

Greater transparency in how climate action will be implemented in *National Adaptation Plans* and *River Basin Management Plans* is needed. Forthcoming plans should state how climate action will integrate across the *Sectoral Adaptation Plans* and continue to consult the Environmental Protection Agency (EPA) and Higher Educational Institutions (HEIs) to **produce more comprehensive and inclusive plans in relation to water governance**.

3) Climate Change Sectoral Adaptation Plans – Review

There are nine *Climate Change Sectoral Adaptation Plans* compiled by seven governmental departments in response to statutory requirements of the *Climate Act 2015* (Table 8.). Each plan follows the guidelines from the *National Adaptation Framework* (NAF) published in 2018 by the Department of the Environment, Climate and Communications. When reviewed together the following findings are as follows:

Table 8. A list of *Climate Change Sectoral Adaptation Plans* and corresponding governmental departments.

Climate Change Sectoral Adaptation Plans	
Sectoral Plan	***Prepared by***
Agriculture, Forest and Seafood	Department of Agriculture, Food and the Marine
Biodiversity	Department of Tourism, Culture, Heritage, Arts, Gaeltacht, Sport and Media
Built and Archaeological Heritage	Department of Tourism, Culture, Heritage, Arts, Gaeltacht, Sport and Media
Communication Networks	Department of Communications, Climate Action and Environment
Electricity and Gas Networks	Department of Communications, Climate Action and Environment
Flood Risk Management	Office of Public Works (OPW)
Health	Department of Health
Transport	Department of Transport, Tourism and Sport
Water Quality and Water Services	Department of Housing, Local Government and Heritage

- **Finding 1:** The *Climate Change Sectoral Adaptation Plan* for *Agriculture, Forest and Seafood* is the **only plan which does not directly link the specific impacts of climate change to expected impacts in relation to water quality** (where applicable). For example, '*slurry storage and land spreading issues*' are identified as an impact but are not directly connected to rapid, high-intensity precipitation events and extended periods of abnormally low precipitation. This link is essential for clear guidelines to be produced for the agricultural sector. Specific impacts are linked in the case study section but not explicitly outlined in Section 4.1 *'Priority Impacts and Consequences'*.
  - ***Recommendation:*** Revise '*Section 4.1 Priority Impacts and Consequences*' (of the *Climate Change Sectoral Adaptation Plan* for *Agriculture, Forest and Seafood)* to include linkages to specific climate change impacts i.e., increased air and water temperatures, extended periods of abnormally low precipitation, rapid, high-intensity precipitation and flooding events, sea level rise, changes in hydrology (flow), increased frequency and intensity of storm activity and storm surge events; in line with other sectoral adaptation plans to provide a clear and comprehensive framework for local authorities and land uses. Technical guidance documents could then be created for each sector to improve understanding and expectations for land users and overall increase efficiency and progression.
- **Finding 2:** A strength of the adaptation plans is that they exhibit **good cross-sectoral alliances**. The *Water Quality and Water Services* plan provides parameters for other plans regarding water quality; however, some discrepancies were found regarding the impact of climate change on water quality in this review. The next section provides suggestions on how to further improve this important adaptation plan.

4) Water Quality and Water Services, Climate Change Sectoral Adaptation Plan – Review

The *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan* prepared by the Department of Housing, Local Government and Heritage, Government of Ireland was first published in October 2019 and revised in November 2021. This plan is the main roadmap for protecting and improving water quality and water services infrastructure in a changing climate and its associated weather dynamics, including impacts on water use.

- **Finding 1:** This **plan is comprehensive** in its approach, five main challenges for water quality are identified (Table 9.). However, based on our scientific literature review (Section 3.0) **several discrepancies are still evident** amongst other impacts listed in this comprehensive plan.

Table 9. A list of five main challenges for water quality outlined in the *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan.*

Water Quality and Water Services, Climate Change Sectoral Adaptation Plan	
1	High rainfall and flooding leading to mobilisation of pollutants.
2	Reduced dilution of contaminants in water bodies at low flow.
3	Increased spread and viability of pathogens, such as from livestock waste and slurry.
4	Drying of peatland resulting in the reduction of natural filtration of pollutants.
5	Changes in the distribution and viability of native, non-native and invasive flora and fauna.

» ***Recommendation:*** The following impacts associated with climate change should be included in the next revision:

i. Increased lake water temperatures will **alter thermal stratification patterns** (lake mixing) resulting in major physical, chemical, and ecological effects in freshwater lakes and thus impacting on water quality, including an acceleration of lake deoxygenation with subsequent effects on nutrient mineralisation and phosphorus release from hypoxic and/or anoxic lake sediments.

ii. **Harmful cyanobacterial blooms** are included with toxic effects impacting aquatic organisms (fish kills); however, the impact on recreational activities (bathing and water sports) and drinking water consumption is not included. Nutrient enrichment and the occurrence of cyanobacterial blooms are listed again in section D as a *medium priority impact chain*.

iii. Groundwater in sensitive karst regions is listed as vulnerable to drought and warmer temperatures, with subsectors including pathogens, nutrients and sediments, pesticides and industrial and emerging pollutants. **Increased contamination and mobilisation of nutrients associated with rapid, high-intensity precipitation events and flooding** should also be included for groundwater in karst regions. This will be a particular issue after extended periods of abnormally low precipitation when contaminants concentrate in surface soils, with rapid, high-intensity precipitation mobilising contaminants to groundwater in a connective pathway. An immediate call for research for chloroform and THM formation (along with other harmful chlorination by-products), as well as the mapping for karst groundwater pathways should be prioritised with high importance for Irish water quality.

iv. **The drying of peatlands and the increase of DOC export** to surface water systems should be included. Drinking water catchments in peatland regions may be particularly impacted due to increased organic matter and dissolved organic carbon concentrations in fluvial forms. This is due to accelerating temperatures and enhanced frequency and severity of extended periods of abnormally low precipitation, which all act to lower water tables and expose peat to increased aeration and leaching of DOC and organic matter. Increased concentrations of DOC in freshwaters originating from peat soils have implications both for the ecology of receiving waters and for the quality and treatment costs of water used for human consumption.

v. **Atmospheric wet deposition of nutrients,** particularly nitrogen and ammonium should be included as a pollutant source in surface waters (Kelleghan *et al.,* 2021). This is a new field of research in Ireland, although international literature is currently present (Luo *et al.,* 2022). The impacts on water bodies should be further investigated as an additional pollutant source, as a research priority area of high importance.

vi. **Marine and freshwater acidification** should be considered as a challenge for climate adaptation. Ocean and freshwater acidification will impact aquatic and marine ecosystems and subsequent food sources; while this cannot be mitigated at a local/regional level, adaptation of economically important species such as shellfish should be considered.

The following recommendations (in Table 10) are proposed for the inclusion in the next version pf the Climate Change Sectoral Adaptation Plans.

Table 10. Recommendations for each *Climate Change Sectoral Adaptation Plan* regarding discrepancies in the impact of climate change on water quality.

Climate Change Sectoral Adaptation Plans – Recommendations	
Sectoral Plan	***Inclusion of…***
Agriculture, Forest and Seafood	• Freshwater acidification and its potential impact on seafood production • Atmospheric nitrogen deposition as an extra-regional source of pollution
Biodiversity	• Cyanobacterial harmful algae blooms • Freshwater acidification • Atmospheric nitrogen deposition in SAC's and SPA's • Elaborate on disease in biodiversity
Flood Risk Management	• Waste water infrastructure and combined sewage overflow systems need to take into account projected changes in regional rainfall patterns. Climate change and aging infrastructure and equipment, along with population rise, will all put pressure on wastewater treatment, which directly affects water quality. Opportunities to minimise flood waters through sustainable urban drainage systems and nature based climate (and water) solutions should be explored. • Prevalence for waterborne disease impact on human health • Comprehensive discussion of the vulnerability of groundwater in karst regions in particular confined sections of flow (delayed response)

	• Saline intrusion and total dissolved solids (TDS)
Health	• Trihalomethanes (THMs) and other harmful by-products from chlorination of surface water used for potable water • More research on projected climate change and the anticipated trajectory of waterborne diseases • Saline intrusion and contamination of drinking water sources with TDS • Cyanobacterial harmful algae blooms in relation to recreational (bathing, sports) tourism and drinking water uses. Aquaculture is the only use included in relation to this variable • Anticipated disruption to bathing water quality from waste water treatment plants and combined sewage overflow systems during flood events, along with mobilised nutrients and contaminant from intensive agricultural land after periods of heavy rain
Transport	• NOx emissions and atmospheric nitrogen deposition

5) Water Services Policy Statement 2018-2025 – Review

The *Water Services Policy Statement 2018-2025* was prepared by the Department of Housing, Local Government and Heritage and published in December 2020, and was revised in April 2021. The goal of the national policy is to provide '*access to safe, reliable and high quality drinking water*', with quality, conservation and future-proofing listed as key policy objectives.

- **Finding 1:** Overall the policy discusses the **planning for 'future proofing' against climate change rather than providing a more progressive action plan**. The plan **does not link specific climate change impacts to water quality concerns**, this will impact local actions due to a lack of clarity. Existing anthropogenic pressures are solely linked to the degradation of water quality. The future-proofing priority objectives for quality and conservation will however be helpful in the mitigation of climate change impacts.
    - » ***Recommendation:*** A review of the Water Services Policy Statement should align with the *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan* for specific impacts on water quality in association with climate change.

- **Finding 2:** Climate change will impact the following environmental concerns i) increased TOC and DOC export and THM formation in surface water used for potable water and ii) saline intrusion specifically in vulnerable karst regions and should not be excluded.
    - » ***Recommendation:*** A revision is required to include the above points.

- **Finding 3:** A strong reliance is placed on the *River Basin Management Plan* 2018-2027, which is currently not sufficient to cope with expected climate change impacts on water bodies. See the *River Basin Management Plan* review for suggested recommendations.

6) National Water Resources Plan – Framework Plan (2021) - Review

The *National Water Resources Plan – Framework Plan (2021)* was prepared by Uisce Éireann in Spring 2021. The plan outlines Uisce Éireann's twenty-five year plan for water assets and is a key document for national policy in relation to drinking water and climate change.

- **Finding 1:** This plan is comprehensive and shows cross-sectoral alliance including reference to:
    - Water Services Policy Statement (WSPS)
    - Project Ireland 2040 – National Planning Framework (NPF)
    - Water Framework Directive (WFD)
    - River Basin Management Plan (RBMP) for Ireland
    - National Adaptation Plan (NAP)
    - Adaptation Plan for Water Quality and Water Services Infrastructure
    - Recast Drinking Water Directive (DWD)
- **Finding 2:** The strength of this plan in terms of water quality lies in the '*Drinking Water Safety Plan and Barrier Assessment approaches*' section (Figure 5.4, page 93) which outlines Uisce Éireann's plan to manage risks to our water supplies (Table 11.).

Table 11. Uisce Éireann's Barriers for Achieving Safe and Secure Drinking Water.

Uisce Éireann's Barriers for Achieving Safe and Secure Drinking Water	
1	Inactivation of bacteria and viruses, as determined from a calculation of the chlorine contact time (generally referred to as 'Ct').
2	Maintenance of a microbiological barrier in the distribution network.
3	Inactivation of protozoa (i.e., *Cryptosporidium* and *Giardia*) by UV radiation with reference to a determination of the Cryptosporidium risk score.
4	Removal of protozoa (i.e., *Cryptosporidium* and *Giardia*) by coagulation, flocculation, and clarification (CFC) and filtration, slow sand filtration or membrane filtration with reference to a determination of the Cryptosporidium risk score.
5	Prevention of supply interruptions.
6	Prevention of the formation of trihalomethanes (THMs).
7	Prevention of pollution of the environment.
8	Minimising the level of other physical / chemical parameters such as: lead, iron, pesticides, nitrates, aluminium, manganese, taste and odour.

» **Finding 3:** The plan refers to the need to understand climate change but does not include information on the specific impacts of climate change on water quality and water treatment.

» ***Recommendation:*** Increased dissolved organic carbon export should be included as an additional barrier in the '*Drinking Water Safety Plan and Barrier Assessment* *approaches*' section, due to associated disinfection-by-product issues with carcinogenic THM formation during the chlorination process. This will be a significant issue for water treatment functioning and cost with climate change.

4.2 Comparison of National Policies and Identification Scientific Knowledge Gaps

This review section visually compares the main environmental impacts of climate change on water quality outlined in Section 3 of the report with the relevant national policies for stakeholders. Tables 12 and 13 identify the gaps in the scientific knowledge amongst national policies, providing an inventory to strengthen plans and subsequently protect our natural resources and aquatic ecosystems from the effects of climate change.

Table 12. A list of national policies showing the year of publication and the number of times the terms 'climate change' and 'water quality' are mentioned. Bold font is used to highlight the underrepresentation of terms in each plan.

		No. of Times Mentioned	
National Policies	**Publication Year**	**Climate Change**	**Water Quality**
Biodiversity Action Plan (Draft, fourth cycle)		13	9
National Adaptation Framework	2018	97	**2**
Water Services Policy Statement 2018-2025	2020	**6**	15
Climate Action Plan	2021	65	10
National Development Plan 2021-2030	2021	28	**8**
National Water Resources Plan – Framework Plan (Uisce Éireann)	2021	33	42
Water Quality and Water Services, National Climate Change Sectoral Adaptation Plan	2021	66	71
River Basin Management Plan 2022-2027 (Draft, third cycle)	2022	**14**	48
Nitrates Action Plan	2022	**3**	23

4.2.1 A SCOT Analysis

A SCOT analysis was completed upon review of the scientific literature, legislation and policy for the impact of climate change on water quality in Ireland. The analysis highlights the current strengths, challenges, opportunities and threats to water quality (Figure 6.).

Table 13. Inventory of Gaps in National Policies Regarding Scientific Knowledge of Climate Change and its Impacts on Water Quality. Asterix indicate the government department responsible for preparing the plans:
* = Uisce Éireann (formerly Irish Water)
** = Department of Housing, Local Government and Heritage

NATIONAL POLICIES		SURFACE AIR AND WATER TEMPERATURE									DRY PERIODS	PRECIPITATION EVENTS			SEA LEVEL RISE		CO2		WIND	
		ALTERED THERMAL STRATIFICATION (LAKES AND COASTAL BODIES)	EXACERBATE EFFECTS OF EUTROPHICATION	HARMFUL CYANOBACTERIAL BLOOMS	DECREASED DISSOLVED OXYGEN	INCREASED DISSOLVED ORGANIC CARBON (DOC) EXPORT	INCREASED PREVALENCE OF WATERBORNE DISEASE	LOSS OF NATIVE COLD-WATER SPECIES	INCREASED INVASIVE SPECIES	TRIHALOMETHANES (THM) FORMATION	CONCENTRATION OF CONTAMINANTS	MOBILISATION OF CONTAMINANTS	MOBILISATION OF WATERBORNE PATHOGENS	ATMOSPHERIC WET DEPOSITION OF NUTRIENTS	SALINE INTRUSION INCREASING TOTAL DISSOLVED SOLIDS	TRIHALOMETHANES (THM) FORMATION	OCEAN ACIDIFICATION	FRESHWATER ACIDIFICATION	CONTAMINANT CIRCULATION	SEDIMENT RESUSPENSION
National Water Resources Plan – Framework Plan *	2021	✗	✗	✗	✗	✗	✗			✗		✗	✗	✗	✗	✗		✗	✗	✗
Water Quality and Water Services Climate Change Sectoral Adaptation Plan **	2021	✗	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✗	✗	✗	✓	✗
River Basin Management Plan 2022-2027 **	2022	✗	✗	✗	✗	✗	✗	✓	✓		✓	✓	✓	✗				✗	✗	✗

Figure 6. SCOT analysis highlighting the strengths, challenges, opportunities, and threats for water quality in Ireland, based on the findings of this report.

SCOT Analysis

Strengths

- The workforce and facilities are currently in place to:
  - Revise legislation and policy
  - Continue monitoring
  - Provide technical guidance documents for local authorities and land users
- Good cross-sectoral alliances are present in the *Climate Change Sectoral Adaptation Plans*
  - The *Water Quality and Water Services* plan is comprehensive

Challenges

- Water quality is not uniformally acknowledged in national policies,
- Climate change is not uniformally acknowledged in EU Directives
- Misalignment and discrepancies are present in national policies due to a lack of communication and collaboration between governmental departments
- National policy actions highlight the early stage of progression in mitigating climate change impacts
- Issues are present regarding management and infrastructure services associated with water quality, i.e. waste water treatment plants and combined sewage overflow systems in urban areas
- Lack of prosecution for defaulters
- Adequate investment

Opportunities

- Incorporate climate change into EU and Irish Legislation to correctly mitigate the impact of climate change
- Improve communication and collaboration with stakeholders as a cost-effective way to address current misalignment and discrepancies issues in national policies
- Fund and expedite strategic research priority areas to address gaps in knowledge present in Irish literature
- Revise the *Water Quality and Water Services, Climate Change Sectoral Adaptation Plan* to include the full breadth of expected impacts from climate change as outlined in this report.

Threats

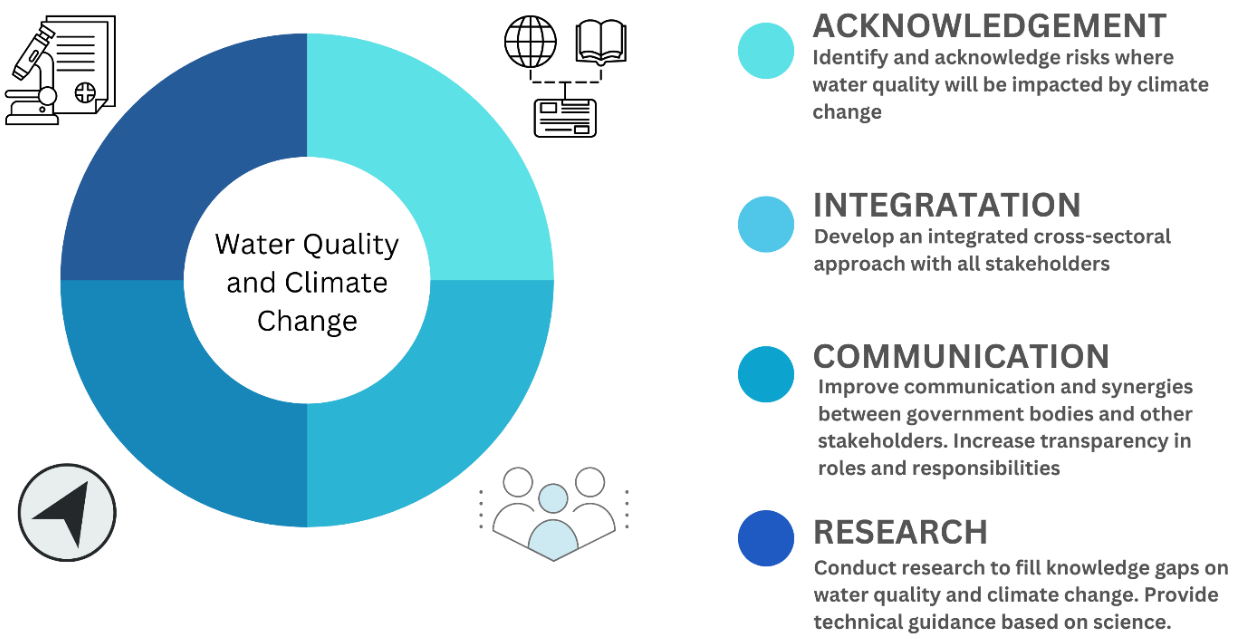
- The cost of drinking water production and issues regarding effective water treatment
- Climate change will exacerbate underlying environmental issues creating a further decline of water quality and aquatic ecosystems, impacting the economy, environment and health and well being, including impacts on:
- Food production i.e. shellfish and fishing industry
- Impact on recreational activities and tourism – bathing and water sports
- Loss of native cold-water species and increase in invasive species
- Prevalence of cyanobacterial harmful algae blooms and eutrophication
- Human health - increased prevelance of waterborne diseases
- Marine and freshwater acidification and its associated impact on aquatic ecosystems

5. Summary – Key Findings and Recommendations

It is essential that international initiatives and national strategies that promote policy responses to the water quality challenge are adaptive to climate change, particularly for the attainment of The 2030 Agenda and Sustainable Development Goals

Water serves many environmental and socioeconomic purposes including: i) **river water and freshwater lakes** are important sources of drinking water (around 82% of potable water in Ireland); provide water for domestic and industrial uses, irrigation and fisheries, and are a common place for recreational activities and swimming; ii) **coastal waters** support society including transportation, tourism, recreation, and fisheries sectors; iii) **groundwater** provides an important drinking water source, particularly for rural communities. Given the importance of water, it is vital that we protect this essential natural resource using the structures we currently have in place. This report illuminates pathways to strengthen, improve and fast-track progression to 'future-proof' Irish water quality in a warmer and less-predictable world. Key recommendations are discussed below and presented in Figure 7.

Figure 7. Key recommendations identified from the report findings.



The main findings of this report are as follows:

1. Acknowledgement

Recommendation 1.1: Identify and acknowledge risks where water quality will be impacted by climate change. The impacts of climate change on water quality should not be addressed in isolation. Drivers of water quality degradation (both individual pressures and climate change) should be addressed in tandem to adequately mitigate environmental impact.

Recommendation 1.2: The Climate Action Plan should be revised. The impacts listed in Box 21.1, Page 202 – Potential Impacts of Climate Change in Ireland, require a significant revision to provide an informed and comprehensive review. Impacts should be identified as 'expected' not 'potential' impacts.

Recommendation 1.3: The Climate Change Adaptation Plans for each sector should be revised and updated with measures where water quality is relevant to the various sectors. Table 10 in the main report outlines the current gaps.

Recommendation 1.4: The Water Quality and Water Services, Climate Change Sectoral Adaptation Plan should be revised and include the following.

- Increased lake water temperatures will alter thermal stratification patterns (lake mixing) resulting in major physical, chemical, and ecological effects in freshwater lakes and thus impacting on water quality, including an acceleration of lake deoxygenation with subsequent effects on nutrient mineralisation and phosphorus release from hypoxic and/or anoxic lake sediments.
- The impact of harmful cyanobacterial blooms on recreational activities
- Increased contamination and mobilisation of nutrients associated with rapid, high-intensity precipitation events and flooding should also be included for groundwater in karst regions.
- The drying of peatlands and the increase of DOC export to surface water systems should be included. Increased concentrations of DOC in freshwaters originating from peat soils have implications both for the ecology of receiving waters and for the quality and treatment costs of water used for human consumption.
- Atmospheric wet deposition of nutrients, particularly nitrogen and ammonium should be included as a pollutant source in surface waters
- Marine and freshwater acidification should be considered as a challenge for climate adaptation. Ocean and freshwater acidification will impact aquatic and marine ecosystems and subsequent food sources; while this cannot be mitigated at a local/regional level, adaptation of economically important species such as shellfish should be considered.

Recommendation 1.5: The National Water Resources Plan should be revised to include increased dissolved organic carbon export should be included as an additional barrier in the 'Drinking Water Safety Plan and Barrier Assessment approaches' section, due to associated disinfection-by-product issues with carcinogenic THM formation during the chlorination process. This will be a significant issue for water treatment functioning and cost with climate change.

Recommendation 1.6: Amendments need to be made to EU legislation (including Urban Wastewater Directive, Bathing Water Directive and Nitrates Directive) to adequately future-proof our water resources and aquatic ecosystems from the effects of climate change. These include:

- Update needed for the Urban Waste Water Treatment directive, Annex 1 "extreme values for the water quality in question shall not be taken into consideration when they are the result of unusual situations such as those due to heavy rain". Climate change projections include increased frequency and intensity of rapid, high-intensity precipitation events and flooding for Ireland and the EU, therefore 'heavy rain' will no longer be an 'unusual event', highlighting the necessity to revise this directive.
- Additionally, in the Urban Waste Water Treatment directive, Annex II, "a marine water body" is considered a "less sensitive area". The recent EPA report on Water Quality in Ireland shows a significant decline in transitional (estuarine) and coastal waters, which indicates that they are sensitive areas.
- Warmer water temperature associated with climate change will exacerbate the formation of harmful cyanobacterial blooms in standing waters. This factor should be included in the management of Bathing Water Quality Directive (2006/7/EC), Annex III bathing water profile.
- The Protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive 91/676/EEC) does not consider surplus nitrogen pollution, which is volatilised into the atmosphere from chemical fertiliser application. Atmospheric nitrogen deposition is a significant extra-regional nutrient source through wet deposition; the exclusion of this process is a fundamental oversight. The lack of inclusion of climate change as an influencing variable on various water-related directives is highlighted in Table 5.

2. Integration

Recommendation 2.1: Develop an integrated cross-sectoral approach with all stakeholders.
Coordinated long-term national strategies for sustainably managing water in the face of climate change must look at water quality and quantity in a holistic way through collaboration with other sectors that develop policies and plans for activities that pose threats to water security.

Recommendation 2.2: National policies should be reviewed and updated to ensure climate action and climate adaptation measures account for impacts on water quality. Government officials responsible for the River Basin Management Plan 2022-2027, Water Quality and Water Services, Climate Change Sectoral Adaptation Plan, Climate Action Plan 2021 and the Nitrates Action Plan should consult and engage with one another for better alignment, with supporting input from the EPA and latest research (Higher Education Institutes).

Recommendation 2.3: There should be better alignment between the Climate Action Plan and the Sustainable Development Goals SDGs:

- SDG targets such as 14.3 ocean acidification, 14.2 protect and restore ecosystems, 14.5 conserve coastal and marine areas and 14.8 increase scientific knowledge, research and technology for ocean health should also be included.
- The Life On Land SDG (15) should also include the following relevant targets, 15.5 Protect Biodiversity and Natural Habitats, 15.8 Prevent invasive alien species on land and in water ecosystems, and 15.9 Integrate ecosystem and biodiversity in governmental planning.

- Various other SDGs relate to the anticipated impacts of water quality from current and projected climate change, including SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production).

3. **Communication**

Recommendation 3.1: Improve communication and synergies between government bodies and other stakeholders. Government departments, higher Education Institutes, regional authorities and consultancies should work together to develop innovative and tailored practical solutions for water and climate related issues.

Recommendation 3.2: Increase transparency in roles and responsibilities among government bodies, state agencies, non-government organisations and any other relevant stakeholders, to ensure accountability for action for climate adaptation measures relevant to water.

4. **Research**

Recommendation 4.1: Conduct research to fill knowledge gaps on water quality and climate change. Provide technical guidance based on science. Funding should be allocated, and research calls expedited to address strategic priority relevant to increasing knowledge on climate change impacts on water quality in Ireland.

Recommendation 4.2: Future research on the exacerbated effects of eutrophication and the presence of cyanobacterial blooms relating to warmer temperatures and modified precipitation. This will have implications for water quality (reduced dissolved oxygen levels, light penetration and increased alkalinity of the water), aquatic organisms (biodiversity) and human health (aquaculture and recreational activities).

Recommendation 4.3: Future research on the anticipated impacts of dissolved organic carbon (DOC) from organic soils and peatlands due to climate change will impact water bodies and resulting contaminant mitigation in drinking water treatment. DOC export is currently not regulated in Irish surface waters and will likely pose a significant issue to the functioning and cost of water treatment processes for human consumption.

Recommendation 4.4: Future research on the influence of atmospheric wet deposition of nutrients e.g., nitrogen and ammonium and subsequent enrichment should be included. The increased nutrient influx will exacerbate the effects of eutrophication and the prevalence of harmful cyanobacterial blooms, amongst other aquatic ecosystem alterations impacting water quality and restoration plans of water bodies.

Recommendation 4.5: Additional research on the impact and projections for:

- groundwater quality (monitoring) in karst regions, regional/local sea level rise monitoring and enhanced understanding of storm activity in Ireland
- extent of saline intrusion in vulnerable groundwater drinking water sources

- chloroform and trihalomethane (THM) formation in response to climate change and water treatment facilities
- marine and freshwater acidification impacts on water quality and aquatic ecosystems

6. Acknowledgements

The authors would like to acknowledge the financial support of An Fóram Uisce. In particular, the authors would like to thank Dr Triona McGrath and Dr Gretta McCarron for their support and advice during the compilation of this report, and review of the final draft.

7. References

Ahern KS, Udy JW, Pointon SM (2006) Investigating the potential for groundwater from different vegetation, soil and landuses to stimulate blooms of the cyanobacterium, *Lyngbya majuscula*, in coastal waters. *Marine and Freshwater Research* **57**, 177-186. DOI: https://doi.org/10.1071/MF05115

Anderson DM, Porter H, Kaoru Y, White AW (2000) Estimated annual economic impacts from harmful algal blooms (HABs) in the United States. Woods Hole Oceanographic Institution. DOI: https://doi.org/10.1575/1912/96

Anderson, D. M., Glibert, P. M., & Burkholder, J. M. (2002). Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*, *25*(4), 704-726. DOI: https://doi.org/10.1007/BF02804901

Andrade L, Boudou M, Hynds P, Chique C, Weatherill J, O'Dwyer J (2022) Spatiotemporal dynamics of Escherichia coli presence and magnitude across a national groundwater monitoring network, Republic of Ireland, 2011–2020. *Science of The Total Environment* 840, 156311. DOI: https://doi.org/10.1016/j.scitotenv.2022.156311

Antoniades D, Crawley C, Douglas MS, Pienitz R, Andersen D, Doran PT, Hawes I, Pollard W, Vincent, WF (2007) Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy. *Geophysical Research Letters*, *34*(18). DOI: https://doi.org/10.1029/2007GL030947

Armstrong, J. B., Fullerton, A. H., Jordan, C. E., Ebersole, J. L., Bellmore, J. R., Arismendi, I., ... & Reeves, G. H. (2021). The importance of warm habitat to the growth regime of cold-water fishes. *Nature Climate Change*, *11*(4), 354-361 DOI: https:// doi.org/10.1038/s41558-021-00994-y

Aráoz R, Molgó J, de Marsac NT (2010) Neurotoxic cyanobacterial toxins. *Toxicon* 56(5), 813-828. DOI: https://doi.org/10.1016/j.toxicon.2009.07.036

Arneth A, Shin YJ, Leadley P, Rondinini C, Bukvareva E, Kolb M, Midgley GF, Oberdorff T, Palomo I, Saito O (2020) Post-2020 Biodiversity Targets Need to Embrace Climate Change. *Proceedings of the National Academy of Sciences* 117(49) 30882. DOI: https://doi.org/10.1073/pnas.2009584117

Aslibekian O, Moles R (2003) Environmental risk assessment of metals contaminated soils at silvermines abandoned mine site, Co Tipperary, Ireland. *Environmental Geochemistry and Health* 25(2), 247-66. DOI: https://doi.org/10.1023/a:1023251102402

Baily A, Rock L, Watson CJ, Fenton O (2011) Spatial and temporal variations in groundwater nitrate at an intensive dairy farm in south-east Ireland: insights from stable isotope data**.** *Agriculture, ecosystems & environment*, 144(11), 308-318. DOI: https://doi.org/10.1016/j.agee.2011.09.007

Bakun A, Black BA, Bograd SJ, Garcia-Reyes M, Miller A J, Rykaczewski RR, Sydeman WJ (2015) Anticipated effects of climate change on coastal upwelling ecosystems. Current Climate Change Reports, 1(2), 85-93. DOI: https://doi.org/10.1007/s40641-015-0008-4

Barbosa MO, Moreira NF, Ribeiro AR, Pereira MF, Silva AM (2016) Occurrence and removal of organic micropollutants: An overview of the watch list of EU Decision 2015/495. *Water Research* 94, 257-279. DOI: https://doi.org/10.1016/j.watres.2016.02.047

Bednaršek N, Feely RA, Howes EL, Hunt BPV, Kessouri F, León, Lischka S, Maas AE, McLaughlin K, Nezlin NP, Sutula M, Weisberg SB (2019) Systematic Review and Meta-Analysis Toward Synthesis of Thresholds of Ocean Acidification Impacts on Calcifying Pteropods and Interactions With Warming. *Frontiers in Marine Science* 6, 227. DOI: https://doi.org/10.3389/fmars.2019.00227

Boezeman D, Wiering M, Crabbé A (2020) Agricultural Diffuse Pollution and the EU Water Framework Directive: Problems and Progress in Governance. *Water* 12(9), 2590. DOI: https://doi.org/10.3390/w12092590

Boxall, A. B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P. D., ... & Williams, R. J. (2009). Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental health perspectives*, *117*(4), 508-514. DOI: https://doi.org/10.1289/ehp.0800084

Cahill MG, Caprioli G, Stack M, Vittori S, James KJ (2011) Semi-automated liquid chromatography–mass spectrometry (LC–MS/MS) method for basic pesticides in wastewater effluents. *Analytical and bioanalytical chemistry 400*(2), 587-594. DOI: https://doi.org/10.1007/s00216-011-4781-1

Cámaro García W, Dwyer N (2021) Research 386: The Status of Ireland's Climate, 2020. Environmental Protection Agency. Wexford. **ISBN:** 978-1-80009-009-5. Available at: https://www.epa.ie/publications/research/climate-change/research-386-the-status-of-irelands-climate-2020.php

Carpenter SR, Caraco NF, Correll DL, Howarth RQ, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8, 559–568. DOI: https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Casal G, Lavender S (2017) Spatio-temporal variability of sea surface temperature in Irish waters (1982–2015) using AVHRR sensor. *Journal of sea research* 129, 89-104. DOI: https://doi.org/10.1016/j.seares.2017.07.006

Castelle B, Dodet G, Masselink G, Scott T (2018) Increased winter-mean wave height, variability and periodicity in the Northeast Atlantic over 1949-2017. *Geophysical Research Letters* 45, 3586-3596. DOI: https://doi.org/10.1002/2017GL076884

Chen X, Wang Y, Ye C, Zhou W, Cai Z, Yang H, Han X (2018) Atmospheric Nitrogen Deposition Associated with the Eutrophication of Taihu Lake. *Journal of Chemistry* 1-10. DOI: https://doi.org/10.1155/2018/4017107

Chislock MF, Doster E, Zitomer RA, Wilson AE (2013) Eutrophication: causes, consequences, and controls in aquatic ecosystems. Nature Education Knowledge 4(4), 10.

Climate Ireland (2022) Essential Climate Information. Accessed on the 11th of October 2022. Available at: https://www.climateireland.ie/#!/tools/climateInformation/essentialClimateInformation

Codd GA, Morrison LF, Metcalf JS (2005) Cyanobacterial toxins: risk management for health protection. *Toxicology Applied Pharmacology* 203, 264–272. DOI: https://doi.org/10.1016/j.taap.2004.02.016

Coffey R, Benham B, Wolfe ML, Dorai-Raj S, Bhreathnach N, O'Flaherty V, Cormican M, Cummins E, (2016) Sensitivity of streamflow and microbial water quality to future climate and land use change in the West of Ireland. *Regional environmental change*, *16*(7), pp.2111-2128. DOI: https://doi.org/10.1007/s10113-015-0912-0

Copernicus (2022) ESTOTC 2021 Overview, Europe in 2021, Lake surface temperatures. Accessed on 20th of August 2022. Available at: https://climate.copernicus.eu/esotc/2021/lake-surface-temperatures

Davis AC, Patterson BM, Grassi ME, Robertson BS, Prommer H, McKinley AJ (2007) Effects of increasing acidity on metal (loid) bioprecipitation in groundwater: column studies. *Environmental science & technology*, 41(20), 7131-7137. DOI: https://doi.org/10.1021/es071122v

Doney SC, Busch SD, Cooley SR, Kroeker KJ (2020) The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. *Annual Review of Environment and Resources* 45(1), 83-112. DOI: https://doi.org/10.1146/annurev-environ-012320-083019

EPA (Environmental Protection Agency) (2020) Ireland's Environment – An Integrated Assessment 2020. Report prepared by: Wall B, Cahalane A, Derham J (eds) EPA, Wexford, Ireland. ISBN: 978-1-84095-953-6. Available at: https://www.epa.ie/publications/monitoring--assessment/assessment/state-of-the-environment/EPA_Irelands_Environment_2020.pdf

EPA (Environmental Protection Agency) (2021a) Research 386: Climate Status Report for Ireland 2020. Report prepared by Walther CA, García C, Dwyer N (eds) EPA, Wexford, Ireland. ISBN: 978-1-80009-009-5. Available at: https://www.epa.ie/publications/research/climate-change/research-386-the-status-of-irelands-climate-2020.php

EPA (Environmental Protection Agency) (2022a) Ireland's Environment: Water. Accessed on the 15th of August 2022. Available online: https://www.epa.ie/our-services/monitoring--assessment/assessment/irelands-environment/water/

EPA (Environmental Protection Agency) (2022b) Drinking Water quality in Public Supplies 2021. Access on the 29th of November 2022. Available online: https://www.epa.ie/publications/compliance--enforcement/drinking-water/annual-drinking-water-reports/EPA_DrinkingWaterQualityinPublicSupplies2021.pdf

EPA (Environmental Protection Agency) (2022c). Water Quality in Ireland 2016 – 2021. Report prepared by: Trodd W, O'Boyle S, Gurrie M (eds) Wexford, Ireland. Accessed on the 25th of October 2022. Available online: https://www.epa.ie/publications/monitoring--assessment/freshwater--marine/water-quality-in-ireland-2016--2021-.php

EPA (Environmental Protection Agency) (2022d). Urban Waste Water Treatment in 2021. Wexford, Ireland. ISBN: 978-1-80009-063-7 Accessed on the 28th of December 2022. Available online: https://www.epa.ie/publications/monitoring--assessment/waste-water/Urban-Waste-Water-Treatment-in-2021-report.pdf

EPA (Environmental Protection Agency) Drinking Water quality in Public Supplies 2020 (2021b) Available online: https://www.epa.ie/publications/compliance--enforcement/drinking-water/annual-drinking-water-reports/drinking-water-quality-in-public-supplies-2020-.php

European Parliament (2022) Legislative train schedule, Revision of the Urban Wastewater Treatment Directive (REFIT). Accessed on the 27th of October 2022. Available at: https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revision-of-the-urban-wastewater-treatment-directive-(refit)

Evans CD, Monteith DT, Cooper DM (2005) Long-term increases in surface water dissolved organic carbon: Observations, possible causes and environmental impacts. *Environmental Pollution* 137, 55–71. DOI: https://doi.org/10.1016/j.envpol.2004.12.031

Fáilte Ireland (2018) open dataset "Accommodation" http://data.gov.ie/dataset/accommodation

Feeley HB, Bruen M, Blacklocke S, Kelly-Quinn M (2013) A regional examination of episodic acidification response to reduced acidic deposition and the influence of plantation forests in Irish headwater streams. *Science of the Total Environment* 443, 173-183. DOI: https://doi.org/10.1016/j.scitotenv.2012.10.074

Fenner N, Freeman C (2011) Drought-induced carbon loss in peatlands. *Nature geoscience* 4, 895–900. DOI: https://doi.org/10.1038/ngeo1323

Feuchtmayr H, Moran R, Hatton K, Connor L, Heyes T, Moss B, Harvey I, Atkinson D (2009) Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental hypertrophic shallow lake mesocosms. *Journal of Applied Ecology* 46, 713-723. DOI: https://doi.org/10.1111/j.1365-2664.2009.01644.x

Funari E, Manganelli M, Sinisi L (2012) Impact of climate change on waterborne diseases. *Annali dell'Istituto superiore di sanita 48*, 473-487. DOI: https://doi.org/10.4415/ann_12_04_13

García-Berthou E, Alcaraz C, Pou-Rovira Q, Zamora L, Coenders G, Feo C (2005) Introduction pathways and establishment rates of invasive aquatic species in Europe. *Canadian Journal of Fisheries and Aquatic Sciences* 62(2), 453-463. DOI: https://doi.org/10.1139/f05-017

Geris J, Comte J, Franchi F, Petros AK, Tirivarombo S, Selepeng AT, Villholth KG (2022) Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. *Journal of Hydrology* 609, 127834. DOI: https://doi.org/10.1016/j.jhydrol.2022.127834

Goonetilleke, A., & Lampard, J. L. (2019). Stormwater quality, pollutant sources, processes, and treatment options. In *Approaches to Water Sensitive Urban Design* (pp. 49-74). Woodhead Publishing. DOI: https://doi.org/10.1016/B978-0-12-812843-5.00003-4

Greer B, McNamee SE, Boots B, Cimarelli L, Guillebault D, Helmi K, Marcheggiani S, Panaiotov S, Breitenbach U, Akçaalan R, Medlin LK (2016) A validated UPLC–MS/MS method for the surveillance of ten aquatic biotoxins in European brackish and freshwater systems. *Harmful Algae* 55, 31-40. DOI: https://doi.org/10.1016/j.hal.2022.102241

Grilli G, Curtis J (2022) Knowledge and awareness of water quality protection issues within local authorities. *Environmental Science & Policy* 135, 46-57. DOI: https://doi.org/10.1016/j.envsci.2022.04.017

Harrison S, McAree C, Mulville W, Sullivan T (2019) The problem of agricultural 'diffuse' pollution: Getting to the point. *Science of The Total Environment* 677, 700-717, DOI: https://doi.org/10.1016/j.scitotenv.2019.04.169

Hejzlar J, Dubrovský M, Buchtele J, Růžička M (2003) The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malše River, South Bohemia). *Science of the Total Environment* 310(1-3), 143-152. DOI: https://doi.org/10.1016/S0048-9697(02)00634-4

Hofstra N (2011) Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. *Current Opinion in Environmental Sustainability 3*(6), 471-479. DOI: https://doi.org/10.1016/j.cosust.2011.10.006

Holt J, Wakelin S, Lowe J, Tinker J (2010) The potential impacts of climate change on the hydrography of the northwest European continental shelf. *Progress in Oceanography* 86(3-4), 361-379. DOI: https://doi.org/10.1016/j.pocean.2010.05.003

HSE (2022) Trihalomethanes in Drinking Water. Accessed on the 25th of September 2022. Available at: https://www.hse.ie/eng/health/hl/water/drinkingwater/trihalomethanes/#:~:text=What%20are%20Trihalomethanes%20(THMs)%3F,water%20that%20is%20being%20treated.

Huebsch M, Fenton O, Horan B, Hennessy D, Richards KG, Jordan P, Goldscheider N, Butscher C, Blum, P (2014) Mobilisation or dilution? Nitrate response of karst springs to high rainfall events. *Hydrology Earth System Science* 18, 4423–4435. DOI: https://doi.org/10.5194/hess-18-4423-2014

Hughes J, Cowper-Heays K, Olesson E, Bell R, Stroombergen A (2021) Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management* 31, 100262. DOI: https://doi.org/10.1016/j.crm.2020.100262

Hutchinson GE, (1957) A treatise on limnology. I. Geography, Physics and Chemistry. New York. John Wiley and Sons, Inc; London: Chapman & Hall Lt.

IPCC Sixth Assessment Report Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022) Report prepared by: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Cambridge University Press. In Press. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Prepared by: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI. Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, DOI: 10.1017/9781009157896

Islam MM, Iqbal MS, D'Souza N, Islam MA (2021) A review on present and future microbial surface water quality worldwide. *Environmental Nanotechnology, Monitoring & Management*, *16*, p.100523. DOI: https://doi.org/10.1016/j.enmm.2021.100523

Jane, S. F., Hansen, G. J., Kraemer, B. M., Leavitt, P. R., Mincer, J. L., North, R. L., ... & Rose, K. C. (2021). Widespread deoxygenation of temperate lakes. *Nature*, *594*(7861), 66-70. DOI: https://doi.org/10.1038/s41586-021-03550-y

Jankowski, T., Livingstone, D. M., Bührer, H., Forster, R., & Niederhauser, P. (2006). Consequences of the 2003 European heat wave for lake temperature profiles, thermal stability, and hypolimnetic oxygen depletion: Implications for a warmer world. *Limnology and Oceanography*, *51*(2), 815-819.DOI: **https://doi.org/10.4319/lo.2006.51.2.0815**

Jones L, Sullivan T, Kinsella B, Furey A, Regan F (2017) Occurrence of Selected Metals in Wastewater Effluent and Surface Water in Ireland. *Analytical Letters* 50(4), 724-737. DOI: https://doi.org/10.1080/00032719.2016.1194854

Kaufman DS, McKay NP (2022) Technical Note: Past and future warming – direct comparison on multi-century timescales. *Climate of the Past* 18, 911–917. DOI: https://doi.org/10.5194/cp-18-911-2022

Kaushal SS, Mayer PM, Vidon P G, Smith RM, Pennino MJ, Newcomer TA, Duan S, Welty C, Belt KT, (2014) Land use and climate variability amplify carbon, nutrient, and contaminant pulses: a review with management implications. *JAWRA Journal of the American Water Resources Association*, *50*(3), 585-614. DOI: https://doi.org/10.1111/jawr.12204

Keegan M, Kilroy K, Nolan D, Dubber D, Johnston PM, Misstear BDR, O'Flaherty V, Barrett M, Gill LW (2014) Assessment of the impact of traditional septic tank soakaway systems on water quality in Ireland. *Water Science and Technology* 70 (4), 634–641. DOI: https://doi.org/10.2166/wst.2014.227

Kelleghan DB, Hayes ET, Everard M, Keating P, Lesniak-Podsiadlo A, Curran TP (2021) Atmospheric ammonia and nitrogen deposition on Irish Natura 2000 sites: Implications for Irish agriculture. *Atmospheric Environment* 261,118611. DOI: https://doi.org/10.1016/j.atmosenv.2021.118611

Kelly S, Moore TN, de Eyto E, Dillane M, Goulon C, Guillard JJ, Lasne E, McGinnity P, Poole R, Winfield IJ, Woolway RI, Jennings E (2020) Warming winters threaten peripheral Arctic charr populations of Europe. *Climatic Change* 163(1), 599-618. DOI: https://doi.org/10.1007/s10584-020-02887-z

Kernan M (2015) Climate change and the impact of invasive species on aquatic ecosystems. *Aquatic Ecosystem Health & Management* 18 (3), 321–333. DOI: https://doi.org/10.1080/14634988.2015.1027636

Kløve B, Ala-Aho P, Bertrand G, Gurdak JJ, Kupfersberger H, Kværner J, Muotka T, Mykrä H, Preda E, Rossi P, Uvo CB, Velasco E, Pulido-Velazquez M (2014) Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology* 518, 250-266. DOI: https://doi.org/10.1016/j.jhydrol.2013.06.037

Kolb C, Pozzi M, Samaras C, Jeanne M, VanBriesen JM (2017) Climate Change Impacts on Bromide, Trihalomethane Formation, and Health Risks at Coastal Groundwater Utilities. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*, *Part A: Civil Engineering* 3(3), 04017006. DOI: https://doi.org/10.1061/AJRUA6.0000904

Kortelainen P, Rantakari M, Huttunen JT, Mattsson T, Alm J, Juutinen S, Larmola T, Silvola J, Martikainen PJ (2006) Sediment respiration and lake trophic state are important predictors of large CO2 evasion from small boreal lakes. *Global Change Biology* 12(8), 1554-1567. DOI: https://doi.org/10.1111/j.1365-2486.2006.01167.x

Kosten S, Huszar VLM, Bécares E, Costa LS, van Donk E, Hansson LA, Jeppesen E, Kruk C, Lacerot G, Mazzeo N, De Meester L, Moss B, Lürling M, Nõges T, Romo S, Scheffer M (2012) Warmer climates boost cyanobacterial dominance in shallow lakes. *Global Change Biology* 18, 118-126. DOI: https://doi.org/10.1111/j.1365-2486.2011.02488.x

Lambert S, Wagner M (2018) Microplastics are contaminants of emerging concern in freshwater environments: an overview. *Freshwater microplastics*, 1-23. DOI: https://doi.org/10.1007/978-3-319-61615-5_1

Lazur A, VanDerwerker T, Koepenick K (2020) Review of Implications of Road Salt Use on Groundwater Quality—Corrosivity and Mobilization of Heavy Metals and Radionuclides. *Water Air Soil Pollution* 231, 474. DOI: https://doi.org/10.1007/s11270-020-04843-0

Li P, Holden J, Irvine B (2016) Prediction of blanket peat erosion across Great Britain under environmental change. *Climatic Change* 134, 177–191. DOI: https://doi.org/10.1007/s10584-015-1532-x

Li P, Holden J, Irvine B, Mu X (2017) Erosion of Northern Hemisphere blanket peatlands under 21st-century climate change. *Geophysical Research Letters* 44, 3615–3623. DOI: https://doi.org/10.1002/2017GL072590

Lloyd-Hughes B (2014) The impracticality of a universal drought definition. T*heoretical and Applied Climatology* 117(3), 607-611. DOI: https://doi.org/10.1007/s00704-013-1025-7

Luo Y, Taylor KJ, Potito AP, Molloy K, Beilman DW, Tang Y (2022) Ecological impacts of N-deposition in a remote, high-elevation lake in the Three River Headwaters Region, Qinghai-Tibetan Plateau. *Journal of Paleolimnology* 1-20. DOI: https://doi.org/10.1007/s10933-022-00266-5

Lugo, A. E., Brown, S., Brinson, M. M., Lugo, A. E., Brinson, M., & Brown, S. (1989). Forested wetlands ecosystems of the world.

Marcé R, George G, Buscarinu P, Deidda M, Dunalska J, de Eyto, E, Flaim G, Grossart HP, Istvanovics V, Lenhardt M, Moreno-Ostos E (2016) Automatic high frequency monitoring for improved lake and reservoir management. *Environmental Science & Technology 50*(20), 10780-10794. DOI: https://doi.org/10.1021/acs.est.6b01604

Marine Institute (2022) Biotoxin Status Map. Available at: http://webapps.marine.ie/HABs/BiotoxinMap

McElwain L, Sweeney J (2003) Climate change in Ireland-recent trends in temperature and precipitation. *Irish Geography* 36(2), 97-111. DOI: https://doi.org/10.1080/00750770309555815

McGrath T, Kivimäe C, Tanhua T, Cave RR, McGovern E (2012) Inorganic carbon and pH levels in the Rockall Trough 1991–2010. *Deep Sea Research Part I: Oceanographic Research Papers* 68, 79-91. DOI: https://doi.org/10.1016/j.dsr.2012.05.011

McGrory ER, Brown C, Bargary N, Williams NH, Mannix A, Zhang C, Henry T, Daly E, Nicholas S, Petrunic BM, Lee M (2017) Arsenic contamination of drinking water in Ireland: a spatial analysis of occurrence and potential risk**.** *Science of the Total Environment* 579, 1863-1875. DOI: https://doi.org/10.1016/j.scitotenv.2016.11.171

McKeown M, Potito AP, Hickey KR (2012) The long-term temperature record from Markree Observatory, County Sligo, from 1842 to 2011. *Irish Geography*, *45*(3), pp.257-282. DOI: https://doi.org/10.1080/00750778.2013.830871

McKeown MM, Potito, AP (2015) Assessing recent climatic and human influences on chironomid communities from two moderately impacted lakes in western Ireland. *Hydrobiologia* 765, 245-263. DOI: https://doi.org/10.1007/s10750-015-2418-7

McManus SL, Coxon CE, Mellander PE, Danaher M, Richards KG (2017) Hydrogeological characteristics influencing the occurrence of pesticides and pesticide metabolites in groundwater across the Republic of Ireland**.** *Science of the Total Environment* 601, 594-602. DOI: https://doi.org/10.1016/j.scitotenv.2017.05.082

Medlin L (2013) Molecular tools for monitoring harmful algal blooms. *Environmental Science and Pollution Research* 20, 6683–6685. DOI: https://doi.org/10.1007/s11356-012-1195-3

Mellander PE, Jordan P (2021) Charting a perfect storm of water quality pressures. *Science of the Total Environment* 787, 147576. DOI: https://doi.org/10.1016/j.scitotenv.2021.147576
Met Éireann (2022) Drought Summary. Accessed on the 24th of October 2022. Available at: https://www.met.ie/drought-summary#:~:text=%E2%80%93%20A%20dry%20spell%20is%20a,mm%20of%20rain%20per%20day.
Millero FJ, Woosley R, DiTrolio B, Waters J (2009) Effect of ocean acidification on the speciation of metals in seawater. *Oceanography*, 22(4), 72-85. DOI: http://www.jstor.org/stable/24861025
Moore WS, Joye SB (2021) Saltwater Intrusion and Submarine Groundwater Discharge: Acceleration of Biogeochemical Reactions in Changing Coastal Aquifers. *Frontiers in Earth Science* 9, 600710. DOI: https://doi.org/10.3389/feart.2021.600710
Morash AJ, Speers-Roesch B, Andrew S, Currie S (2021) The physiological ups and downs of thermal variability in temperate freshwater ecosystems. *Journal of Fish Biology* 98(6), 1524-1535. DOI: https://doi.org/10.1111/jfb.14655
Morato T, González-Irusta JM, Dominguez-Carrió C, Wei CL, Davies A, Sweetman AK, Taranto GH, Beazley L, García-Alegre A, Grehan A, Laffargue P (2020) Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. *Global Change Biology* 26(4), 2181-2202. DOI: https://doi.org/10.1111/gcb.14996
Morgan D, Xiao L, McNabola A (2017) Evaluation of combined sewer overflow assessment methods: case study of Cork City, Ireland. *Water and Environment Journal* 31(2), 202-208. DOI: https://doi.org/10.1111/wej.12239
Morrissey P, Nolan P, McCormack T, Johnston P, Naughton O, Bhatnagar S, Gill L (2021) Impacts of climate change on groundwater flooding and ecohydrology in lowland karst. *Hydrology and Earth System Sciences* 25, 1923–1941. DOI: https://doi.org/10.5194/hess-25-1923-2021
Moss, B., Kosten, S., Meerhoff, M., Battarbee, R. W., Jeppesen, E., Mazzeo, N., ... & Scheffer, M. (2011). Allied attack: climate change and eutrophication. *Inland waters*, *1*(2), 101-105. DOI: https://doi.org/10.5268/IW-1.2.359
Moss B (2008) Water pollution by agriculture. *Philosophical Transactions of the Royal Society B* 363, 659–666. DOI: https://doi.org/10.1098/rstb.2007.2176
Murphy C, Charlton R (2008) Climate Change and Water Resources. In: Climate Change – Refining the Impacts for Ireland (2001-CD-C3-M1). EPA STRIVE Programme 2007–2013 (177). Environmental Protection Agency, Co. Wexford, pp. 39-81. ISBN 978-1-84095-297-1
Musacchio A, Andrade L, O'Neill E, Re V, O'Dwyer J, Hynds PD (2021) Planning for the health impacts of climate change: Flooding, private groundwater contamination and waterborne infection–A cross-sectional study of risk perception, experience and behaviours in the Republic of Ireland. *Environmental Research 194*, 110707. DOI: https://doi.org/10.1016/j.envres.2021.110707
Naden PS, Allott N, Arvola L, Järvinen, M, Jennings E, Moore K, Nic Aonghusa C, Pierson D, Schneiderman E (2010) Modelling the impacts of climate change on dissolved organic carbon. In The impact of climate change on European lakes (pp. 221-252). Springer, Dordrecht. DOI: http://dx.doi.org/10.1007/978-90-481-2945-4_13
Naughton O, Johnston P, McCormack T, Gill L (2017) Groundwater flood risk mapping in lowland karst. *Flood Risk Management* 10(1), 53-64. DOI: https://doi.org/10.1111/jfr3.12145
Nazari-Sharabian M, Ahmad S, Karakouzian M (2018) Climate Change and Eutrophication: A Short Review. *Engineering, Technology and Applied Science Research* 8(6), 3668-3672. DOI: https://doi.org/10.48084/etasr.2392
Nguyen LN, Meijer HA, Van Leeuwen C, Kers BA, Scheeren HA, Jones AE, Brough N, Barningham T, Pickers PA, Manning AC, Luijkx IT (2022) Two decades of flask observations of atmospheric δ (O 2⁄ N 2), CO 2, and APO at stations Lutjewad (the Netherlands) and Mace Head (Ireland), and 3 years from Halley station (Antarctica). *Earth System Science Data* 14(2), 991-1014. DOI: https://doi.org/10.5194/essd-14-991-2022

Nieminen, M., Sarkkola, S., Sallantaus, T., Hasselquist, E. M., & Laudon, H. (2021). Peatland drainage-a missing link behind increasing TOC concentrations in waters from high latitude forest catchments?. *Science of the Total Environment*, *774*, 145150. DOI: https://doi.org/10.1016/j.scitotenv.2021.145150

Nolan P, Flanagan J (2020) Report 339: High-resolution Climate Projections for Ireland - A Multi-model ensemble approach. Environmental Protection Agency. Wexford. Available at: https://www.epa.ie/publications/research/climate-change/Research_Report_339_Part1.pdf

North, R. P., North, R. L., Livingstone, D. M., Köster, O., & Kipfer, R. (2014). Long-term changes in hypoxia and soluble reactive phosphorus in the hypolimnion of a large temperate lake: consequences of a climate regime shift. *Global change biology*, *20*(3), 811-823. DOI: https://doi.org/10.1111/gcb.12371

Nzangya JM, Ndunda EN, Bosire GO, Martincigh BS, Nyamori VO (2021) Polybrominated Diphenyl Ethers (PBDEs) as Emerging Environmental Pollutants: Advances in Sample Preparation and Detection Techniques. In Emerging Contaminants. London, UK: IntechOpen.

O'Connor P, Murphy C, Matthews T, Wilby RL (2022) Historical droughts in Irish catchments 1767–2016. *International Journal of Climatology*. DOI: https://doi.org/10.1002/joc.7542

O'Driscoll C, Ledesma JL, Coll J, Murnane JG, Nolan P, Mockler EM, Futter MN, Xiao LW (2018) Minimal climate change impacts on natural organic matter forecasted for a potable water supply in Ireland. *Science of the Total Environment* 630, 869-877. DOI: https://doi.org/10.1016/j.scitotenv.2018.02.248

O'Dwyer J, Chique C, Weatherill J, Hynds P (2021) Impact of the 2018 European drought on microbial groundwater quality in private domestic wells: A case study from a temperate maritime climate. *Journal of Hydrology* 601, 126669. DOI: https://doi.org/10.1016/j.jhydrol.2021.126669

O'Driscoll C, McGillicuddy E, Croot P, Bartley P, McMyler J, Sheahan J, Morrison L (2020). Tracing sources of natural organic matter, trihalomethanes and metals in groundwater from a karst region. *Environmental Science and Pollution Research*, 27(11), 12587-12600. DOI: https://doi.org/10.1007/s11356-020-07855-9

Paerl HQ, Scott JT (2010) Throwing Fuel on the Fire: Synergistic Effects of Excessive Nitrogen Inputs and Global Warming on Harmful Algal Blooms. *Environmental Science & Technology 44* (20), 7756-7758. DOI: https://doi.org/10.1021/es102665e

Paerl HW, Hall NS, Calandrino ES (2011) Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment* 409, 1739-1745. DOI: https://doi.org/10.1016/j.scitotenv.2011.02.001

Paerl HW, Gardner WS, Havens KE, Joyner AR, McCarthy MJ, Newell SE, Boqiang Q, Scott JT (2016) Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae*, 54 213-222. DOI: https://doi.org/10.1016/j.hal.2015.09.009

Paerl HW, Huisman J (2008) Blooms like it hot. *Science* 320, 57–58. DOI: https://doi.org/10.1126/science.1155398

Palviainen M, Finér L, Laurén A, Mattsson T, Högbom L (2015) A method to estimate the impact of clear-cutting on nutrient concentrations in boreal headwater streams. Ambio, 44(6), 521-531. DOI: https://doi.org/10.1007/s13280-015-0635-y

Pan SY, He KH, Lin KT, Fan C, Chang CT (2022) Addressing nitrogenous gases from croplands toward low-emission agriculture. *npj Climate and Atmospheric Science*, *5*(1), 1-18. DOI: https://doi.org/10.1038/s41612-022-00265-3

Paul VJ (2008) Global warming and cyanobacterial harmful algal blooms. In: Hudnell, H.K. (Ed.), Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs, Advances in Experimental Medicine and Biology, vol. 619. Springer, pp. 239–257.

Pavlis M, Cummins E (2014) Using total organic carbon for the assessment of groundwater vulnerability in karst regions at regional scales. *Environmental earth sciences* 72(6), 1993-2007. DOI: https://doi.org/10.1007/s12665-014-3415-2

Peeters F, Straile D, Lorke A, Livingstone DM (2007) Earlier onset of the spring phytoplankton bloom in lakes of the temperate zone in a warmer climate. *Global Change Biology* 13, 1898–1909. DOI: https://doi.org/10.1111/j.1365-2486.2007.01412.x

Peng JF, Song YH, Yuan P, Cui XY, Qiu GL (2009) The remediation of heavy metals contaminated sediment. *Journal of hazardous materials* 161(2-3), 633-640. DOI: https://doi.org/10.1016/j.jhazmat.2008.04.061

Pletterbauer F, Melcher A, Graf W (2018) Climate change impacts in riverine ecosystems. Riverine Ecosystem Management. Aquatic Ecology Series, 8, 203-223. DOIL https://doi.org/10.1007/978-3-319-73250-3_11

Prata JC (2018) Microplastics in wastewater: State of the knowledge on sources, fate and solutions. *Marine Pollution Bulletin* 129, 262-265. DOI: https://doi.org/10.1016/j.marpolbul.2018.02.046

Prowse T, Alfredsen K, Beltaos S, Bonsal B, Duguay C, Korhola A, McNamara J, Vincent WF, Vuglinsky V, Weyhenmeyer GA (2011) Arctic freshwater ice and its climatic role. *Ambio*, 40(1), 46-52. DOI: https://doi.org/10.1007/s13280-011-0214-9

Pugh DT, Bridge E, Edwards R, Hogarth P, Westbrook G, Woodworth PL, McCarthy GD (2021) Mean sea level and tidal change in Ireland since 1842: a case study of Cork. *Ocean Science* 17(6), 1623-1637. DOI: https://doi.org/10.5194/os-17-1623-2021

Qadri F, Khan AI, Faruque ASG, Begum YA, Chowdhury F, Nair GB, Salam MA, Sack DA, Svennerholm, AM (2005) Enterotoxigenic Escherichia coli and Vibrio cholerae diarrhea, Bangladesh, 2004. *Emerging infectious diseases 11*(7), 1104. DOI: https://doi.org/10.3201%2Feid1107.041266

Regnier P, Friedlingstein P, Ciais P, Mackenzie FT, Gruber N, Janssens IA, Laruelle GG, Lauerwald R, Luyssaert S, Andersson AJ, Arndt S (2013) Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature geoscience* 6(8), 597-607. DOI: https://doi.org/10.1038/ngeo1830

Ritson JP, Graham NJD, Templeton MR, Clark JM, Gough R, Freeman C (2014) The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: A UK perspective. *Science of the Total Environment* 473, 714-730. DOI: https://doi.org/10.1016/j.scitotenv.2013.12.095

Rosenfeld PE, Feng LGH (2011) 16 - Emerging Contaminants. *Risks of Hazardous Wastes*, 215-222, DOI: https://doi.org/10.1016/B978-1-4377-7842-7.00016-7

Ruiz-Navarro A, Gillingham PK, Britton JR (2016) Predicting shifts in the climate space of freshwater fishes in Great Britain due to climate change. *Biological Conservation* 203, 33-42 DOI: https://doi.org/10.1016/j.biocon.2016.08.021

Schijven J, Bouwknegt M, de Roda Husman AM, Rutjes S, Sudre B, Suk JE, Semenza JC (2013) A decision support tool to compare waterborne and foodborne infection and/or illness risks associated with climate change. *Risk Analysis*, *33*(12), pp.2154-2167. DOI: https://doi.org/10.1111/risa.12077

Schmidtko, S., Stramma, L., & Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. *Nature*, *542*(7641), 335-339. DOI: https://doi.org/10.1038/nature21399

Sellner KG, Rensel JE (2018) Prevention, control, and mitigation of harmful algal bloom impacts on fish, shellfish, and human consumers. *Harmful Algal Blooms: A compendium Desk Reference*, 435-492. DOI: https://doi.org/10.1002/9781118994672.ch12

Semenza JC, Herbst S, Rechenburg A, Suk JE, Höser C, Schreiber C, Kistemann T (2012) Climate change impact assessment of food-and waterborne diseases. *Critical reviews in environmental science and technology*, 42(8), 857-890. DOI: https://doi.org/10.1080/10643389.2010.534706

Shoari Nejad A, Parnell AC, Greene A, Kelleher BP, McCarthy G (2020) Recent sea level rise on Ireland's east coast based on multiple tide gauge analysis. *Ocean Science Discussions*, 1-26. DOI: https://doi.org/10.5194/os-2020-81

Speight JG (2020) 5 - Sources of water pollution. Natural Water Remediation 165-198. DOI: http://dx.doi.org/10.1016/B978-0-12-803810-9.00005-X

Steele-Dunne S, Lynch P, McGrath R, Semmler T, Wang S, Hanafin J, Nolan P (2008) The impacts of climate change on hydrology in Ireland. *Journal of Hydrology* 356, 28-45. DOI: https://doi.org/10.1016/j.jhydrol.2008.03.025

Sterk A, de Man H, Schijven JF, de Nijs T, de Roda Husman AM (2016) Climate change impact on infection risks during bathing downstream of sewage emissions from CSOs or WWTPs. *Water research*, *105*, pp.11-21. DOI: https://doi.org/10.1016/j.watres.2016.08.053

Stevanović Z, Stevanović AM (2021) Monitoring as the Key Factor for Sustainable Use and Protection of Groundwater in Karst Environments—An Overview. *Sustainability* 13(10), 5468. DOI: https://doi.org/10.3390/su13105468

Strungaru SA, Jijie R, Nicoara M, Plavan G, Faggio C (2019) Micro-(nano) plastics in freshwater ecosystems: abundance, toxicological impact and quantification methodology. *TrAC trends in analytical chemistry*, 110, 116-128. DOI: https://doi.org/10.1016/j.trac.2018.10.025

Svirčev ZB, Tokodi N, Drobac D, Codd GA (2014) Cyanobacteria in aquatic ecosystems in Serbia: effects on water quality, human health and biodiversity. *Systematics and biodiversity* 12(3), 261-270. DOI: https://doi.org/10.1080/14772000.2014.921254

Swindles, G. T., Morris, P. J., Mullan, D. J., Payne, R. J., Roland, T. P., Amesbury, M. J., ... & Warner, B. (2019). Widespread drying of European peatlands in recent centuries. *Nature Geoscience*, *12*(11), 922-928. DOI: https://doi.org/10.1038/s41561-019-0462-z

Tammeorg O, Nürnberg G, Niemistö J, Haldna M, Horppila J (2020) Internal phosphorus loading due to sediment anoxia in shallow areas: implications for lake aeration treatments. *Aquatic sciences* 82(3), 1-10. DOI: https://doi.org/10.1007/s00027-020-00724-0 F

Tedd KM, Coxon CE, Misstear BDR, Daly D, Craig M, Mannix A, Williams NH (2014) An integrated pressure and pathway approach to the spatial analysis of groundwater nitrate: a case study from the southeast of Ireland. *Science of the Total Environment*, 476, 460-476. DOI: https://doi.org/10.1016/j.scitotenv.2013.12.085

Valdivia-Garcia M, Weir P, Graham DW et al. (2019) Predicted Impact of Climate Change on Trihalomethanes Formation in Drinking Water Treatment. *Scientific Reports* 9, 9967. DOI: https://doi.org/10.1038/s41598-019-46238-0

Van Metre PC, Frey JW, Musgrove M, Nakagaki N, Qi S, Mahler BJ, Wieczorek ME, Button DT (2016) High nitrate concentrations in some Midwest United States streams in 2013 after the 2012 drought. *Journal of Environmental Quality* 45(5), 1696-1704. DOI: https://doi.org/10.2134/jeq2015.12.0591

Wang S, McGrath R, Hanafin J, Lynch P, Semmler T, Nolan P (2008) The Impact of Climate Change on Storm Surge over Irish Waters. *Ocean Modelling* 25. 83-94. DOI: https://doi.org/10.1016/j.ocemod.2008.06.009

Watson SB (2003) Cyanobacterial and eukaryotic algal odour compounds: signals or by-products? A review of their biological activity. Phycologia, 42(4), pp.332-350. DOI: https://doi.org/10.1080/14772000.2014.921254

Weatherhead EK, Howden NJK (2009) The relationship between land use and surface water resources in the UK. *Land use policy* 26, S243-S250. DOI: https://doi.org/10.1016/j.landusepol.2009.08.007

Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ (2009) A review of the potential impacts of climate change on surface water quality. *Hydrological sciences journal* 54(1), 101-123. DOI: https://doi.org/10.1623/hysj.54.1.101

Willuweit, L., O'Sullivan, J. J., & Shahumyan, H. (2016). Simulating the effects of climate change, economic and urban planning scenarios on urban runoff patterns of a metropolitan region. *Urban Water Journal*, *13*(8), 803-818. DOI: https://doi.org/10.1080/1573062X.2015.1036086

Withers PJA, Neal C, Jarvie HP, et al., (2014) Agriculture and eutrophication: where do we go from here? *Sustainability* 6, 5853–5875. DOI: https://doi.org/10.3390/su6095853

Woolway RI, Sharma S, Smol JP (2022) Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience*, biac052, DOI: https://doi.org/10.1093/biosci/biac052

Woolway RI, Sharma S, Weyhenmeyer GA, Debolskiy A, Golub M, Mercado-Bettín D, Perroud M, Stepanenko V, Tan Z, Grant L, Ladwig R (2021) Phenological shifts in lake stratification under climate change. *Nature Communications* 12, 2318. DOI: https://doi.org/10.1038/s41467-021-22657-4

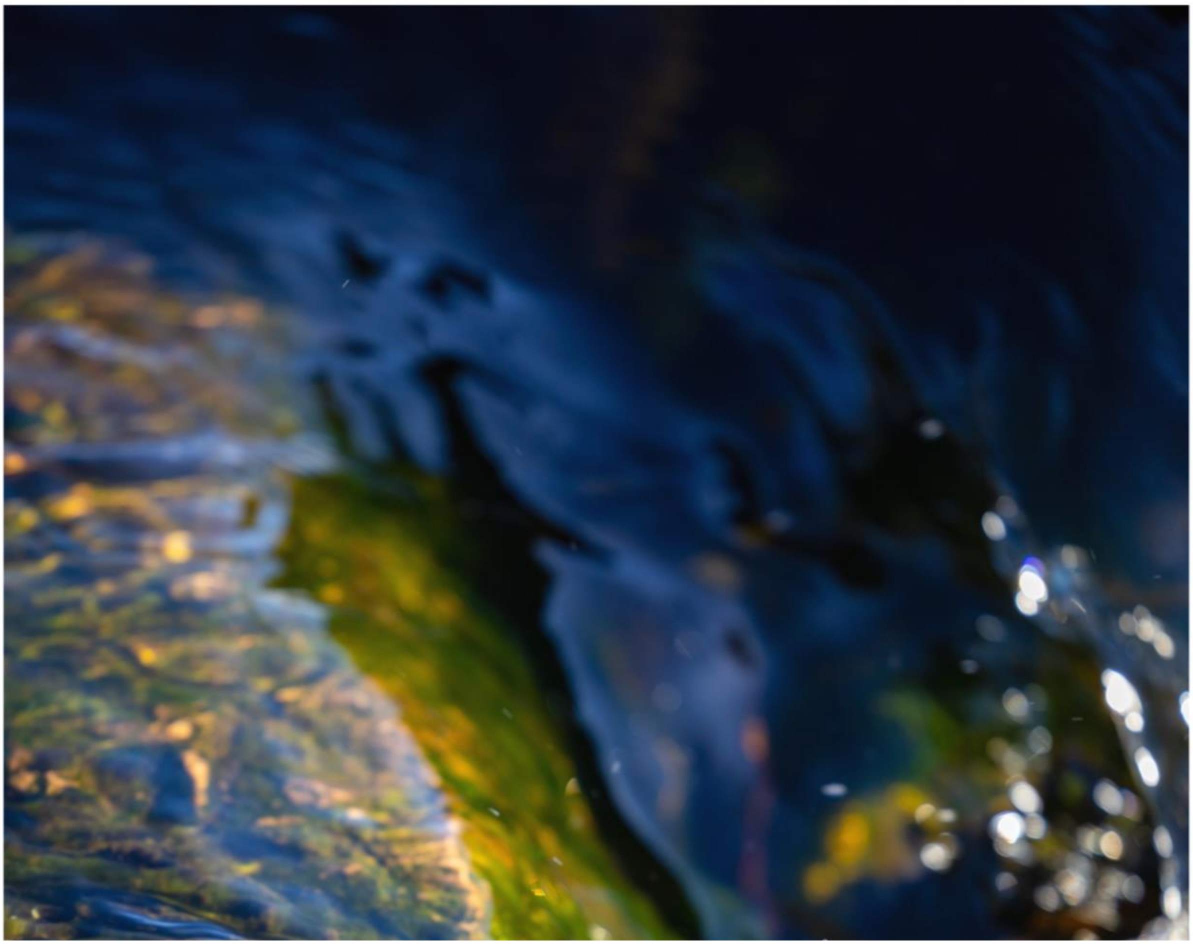
Woolway RI, Weyhenmeyer GA, Schmid M, Dokulil MT, de Eyto E, Maberly SC, May L, Merchant CJ, (2019) Substantial increase in minimum lake surface temperatures under climate change. *Climatic Change* 155(1), 81-94. DOI: https://doi.org/10.1007/s10584-019-02465-y

Xu J, Morris PJ, Liu J, Holden J (2018) Hotspots of peatland-derived potable water use identified by global analysis. *Nature Sustainability*, 1(5), 246-253. DOI: https://doi.org/10.1038/s41893-018-0064-6

Yang Q, Zhang X, Xu X, Asrar GR (2017) An analysis of terrestrial and aquatic environmental controls of riverine dissolved organic carbon in the conterminous United States. *Water* 9(6), 383. DOI: http://dx.doi.org/10.3390/w9060383

Yu F, Shi W (2015) Nitrogen use efficiencies of major grain crops in china in recent 10 years. *Acta Pedologica Sinica* 52, 1311-1324

Zurawell RW, Chen H, Burke JM, Prepas EE (2005) Hepatotoxic cyanobacteria: a review of the biological importance of microcystins in freshwater environments. *Journal of Toxicology and Environmental Health* Part B, 8(1), 1-37. DOI: https://doi.org/10.1080/10937400590889412



This report has been compiled for An Fóram Uisce (the Water Forum)